

**COMPARATIVE ASSESSMENT OF SOIL PHOSPHATE STATUS,  
WATER EUTROPHICATION, AND POTENTIALLY TOXIC METAL  
ACCUMULATION IN USANGU AGRO-ECOSYSTEM**

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Doctor of Philosophy in Life Sciences of the Nelson Mandela African Institution of Science  
and Technology**

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## ABSTRACT

The present study assessed (i) soil fertility, phosphate status, sorption capacity and saturation, (ii) accumulation and distribution of potentially toxic elements (PTEs) in soils and plants, and (iii) soil and surface water quality as they are influenced by current farming practices in Usangu agro-ecosystem (UA) following increased agricultural intensification and urbanization. Soil, sediment, plant, and water sample were collected from ten irrigation schemes for plant nutrients, physico-chemical soil properties, PTEs, water quality determination and assessment. The results indicated that 90% of studied soils had N, P, K, Mg and most micronutrients (Cu and Zn) in deficient levels compared to recommended levels. To ensure sustainable intensification of agricultural production, additional fertilization is recommended. The P soil sorption capacity (PSC), P saturation status (PSD) and its determinants (inherent P ( $P_{M3}$ ),  $Al_{M3}$ ,  $Fe_{M3}$ , and  $Ca_{M3}$ ) which influence P availability, storage, and P losses to the environment determined in UA, were in a range (mg/kg) of:  $P_{M3}$  (14.9-974.7),  $Al_{M3}$  (234.7-3789.4),  $Fe_{M3}$  (456.9-2980.2), and  $Ca_{M3}$  (234.7-973.3). Where estimated  $PSC_{M3}$  ranged 5.6-34.9 mmol/kg, indicating low to high status for P holding or fixation. Some soils had very low  $PSC_{M3}$  indicating a risk of P loss to environment. The estimated  $PSD_{M3}$  ranged from 0.01-17.6% and was less than 24%, indicating low P loss risk from farmlands to water bodies. Some of studied soils had  $PSD_{M3}$  above 15%, which is equivalent to 25% based on ammonium-oxalate method, which can cause higher P loss risk. The spatial PTEs distribution in soils in paddy, maize farming, and conservation areas across contrasting land management schemes (Group I dominated by agricultural areas versus Group II dominated by residential and agricultural areas) varied significantly ( $P < 0.05$ ) across groups and land use. Where total and bioavailable concentrations (in  $\mu\text{g/kg}$ ) of some PTEs determined were; Cr (Group I = 1662 and Group II = 1307 (Total), Group I = 55.1 and Group II = 19.2 (bioavailable)) and Pb (Group I = 5272 and Group II = 6656 (Total), Group I = 1870 and Group II = 1730 (bioavailable)). Farming areas had higher PTEs concentrations than non-farming areas. Overall, concentrations of Fe (99.5%), As (87%), Se (66%) and Hg (12%) were above Tanzanian maximum permissible limits. Furthermore, water quality and eutrophication characterization in UA observed water pH ranging 4.9 to 6.8, where some were outside FAO acceptable range (6.5-8.4) for irrigation water. The  $NH_4\text{-N}$  ranged 10.6-70,  $NO_3\text{-N}$  (8.4-33) and total N (19.1-104 mg/L), which increased as water moved from intakes to drainages. Whilst total P ranged 0.01-1.65 mg/L and increased from intake to drainages and in some sampling points exceeding 0.1 mg/L indicating water quality degradation.

## DECLARATION

I, Marco Mng'ong'o, do hereby declare to the Senate of Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.



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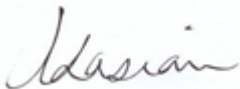
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## CERTIFICATION

The undersigned certify that have read and hereby accept the dissertation titled “Comparative Assessment of Soil Phosphate Status, Water Eutrophication and Potentially Toxic Metal Accumulation in Usangu Agro-ecosystem” in fulfilment of the requirements for the Degree of Doctor of Philosophy in Life Sciences-Sustainable Agriculture (LiSBE) at the Nelson Mandela African Institution of Science and Technology (NM-AIST).



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## **DEDICATION**

This thesis is dedicated to Sustainable Agriculture and Environmental Conservation Community  
in Tanzania

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## LIST ABBREVIATIONS

AQ	Aqua regia
ATP	Adenosine triphosphate
BCF	Bioconcentration factor
DPS	Downstream part of Usangu basin
EC	Electrical conductivity
EPC	Equilibrium phosphate concentration
FAO	Food and agriculture organization
HCl	Hydrochloric acid
HNO <sub>3</sub>	Nitric acid
M3	Mehlich 3 extraction method
MPS	Middle part of Usangu basin
NH <sub>4</sub> -N	Ammonium nitrogen
NO <sub>3</sub> -N	Nitrate nitrogen
OC	Organic carbon
°C	Degree celsius
OM	Organic matter
P	Phosphorus
PLI	Pollution load index
PSC	Phosphate sorption capacity
PSD	Phosphate saturation degree
PTEs	Potentially toxic elements
PTMs	Potentially toxic metals
Er	Ecological risks
SHT	Southern Highland Tanzania
TANAPA	Tanzania National Parks
TAZAM	Tanzania and Zambia Highway

## CHAPTER ONE

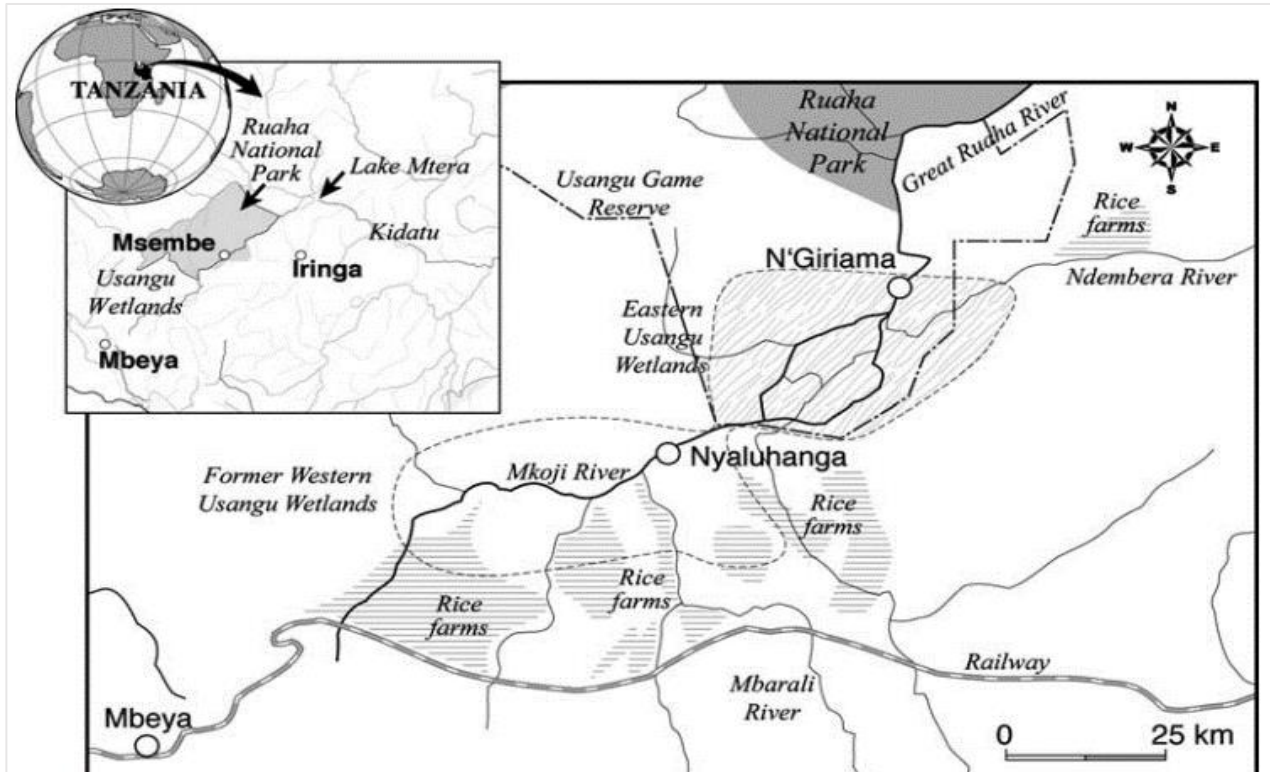
### INTRODUCTION

#### 1.1. Background of the problem

To ensure sustainable use and management of soil and surface water resources in agro-ecosystems requires a better understanding and knowledge of historical impacts and future changes on soil and water quality. A better understanding of urbanization, population increase, agriculture intensification, surface-water flow pathways and their interactions helps develop usable land and water management options for enhanced agro-ecosystem productivity, environmental quality, and sustainability in the landscape. Thus, how future land use, urbanization, and agricultural intensification will interact with agro-ecosystems (AE) to affect soil and water quality, land productivity, and sustainability in AE deserves more attention. Socio-economic transitions and population growth are driving the need for urbanization and agricultural intensification (Behera *et al.*, 2012). Such drivers include agricultural expansion through forest lands clearing, increased croppings per season, and increased agrochemicals use for higher yields required to meet increased food demand. The increasing population consequently increases the demand for shelter, nutrition, and water for various purposes, increasing pressure on forests, farmlands, and water resources. The lack of a sustainable management plan, can lead to negative environmental impacts, such as shortages of fresh water and water quality degradation; soil quality degradation (physical and chemical, i.e., nutrient loss and contamination by potentially toxic metal(oids)s); deforestation and loss of biodiversity (Ezeh *et al.*, 2012).

Usangu basin (USB) is situated in Mbeya region in Southern Highland Tanzania and is the upper part of Rufiji river basin and has an area of about 20 800 km<sup>2</sup> (Fox, 2004; Kashaigili *et al.*, 2006). Generally, USB includes floodplains in the valleys near the river (where water concentrates) and the mountain ranges, which are the major sources of the water and runoff from the towns; but also receives rainwater runoffs generated from towns along TAZAM (Tanzania and Zambia Highway), TAZARA (Tanzania and Zambia Railway Authority line), and Mbeya city. The USB has extensive river networks, including eight main rivers (such as little Ruaha, Kimani, Mkoji, Mbarali, Ndembera, and Chimala), used for irrigation farming (especially paddy rice and horticultural

crops). Thus, supports rainfed and irrigation farming in mid and lowlands parts of USB (Fig. 1). In addition, water in the lowlands supports wildlife in Ihefu and Ruaha national park.



**Figure 1: The Usangu plains showing rice farms and rivers sources for irrigation which also are contributors to the Great Ruaha River (GRR) (Mtahiko *et al.*, 2006)**

Until 1960s, USB was mainly for pastoralists and animal grazing with communal land ownership. However, in the early 1980s, Tanzania government organized an irrigation project and opened three large paddy rice farms (Kapunga, Madibira, and Rujewa), which utilized water from different rivers found in the area originating from the western mountains. This scenario caused some former pastoralists and animal grazing communities to shift to paddy rice farming. As a result, USB has irrigated farms ranging from 40 933 ha to 42 812 ha during the wet season of the normal year. The USB produces 10 to 14% of rice consumed in Tanzania and extends to form Rufiji river basin and Great Ruaha River (GRR) network. Generally, Usangu basin is divided into three parts:

- (i) The Upper Usangu (UPS) part is characterized by mountainous and undulating slopes with altitudes ranging 1 100 to 2 210 m.a.s.l and an average rainfall range of 1 000 to 1700 mm per year; this area is where TAZAM and TAZARA pass. It is associated with dramatic increasing settlement, urbanization, and industrialization. The area has small

to medium processing industries; along this area (UPS), some mining activities of common minerals such as gravel, sand, calcites, and previous artisanal gold mining existed (i.e., at Igalako and Mabadaga). In the far upper of this area is the mountainous national reserved area under TANAPA (Tanzania National Parks). All rivers and drainage channels from Kipengele and Poroto mountains and runoffs from Mbeya towns pass through UPS to the middle and lowland of USB.

- (ii) The middle part of Usangu basin (MPS) is composed of a wide flat plain with fluvial soils materials with frequent flooding during the rainy season (December to March), with altitudes ranging 910 to 1 100 m.a.s.l and average rainfall range of 500 to 700 mm per year. The area receives water from all rivers and temporary rivers, which transport surface water runoffs from the upper part of the basin. The area is dominated by small and large irrigation farms where paddy rice, potatoes, maize, and horticultural crops are mainly grown. In this part, water from rivers and drainage channels from UPS is utilized in irrigated farming, where water is diverted from rivers to farms through constructed irrigation channels (paved and unpaved). In this area, water ponding in agricultural fields, especially paddy fields, is about 10-25 cm in depth during cropping season (December to May). The flowing water over agricultural fields is likely to mobilize and export plant nutrients and other agrochemical residuals downstream, affecting agro-ecosystem productivity and sustainability.
- (iii) The downstream part of the basin (DPS): The area has altitude ranging 800 to 1 000 m.a.s.l and average rainfall range of 500 to 700 mm per year. Which later converges into a narrow natural basin forming a Great Ruaha River network which flows to Mtera and Kidatu dams. The downstream parts also host conservation wildlife areas, i.e., Ruaha national park and other rural towns such as Madibira, Idodi, and Iringa. The community and inhabitants' livelihood in the area is directly influenced by UPS and MPS activities which drive water flow, quality, and contaminants in soil and water.

Irrigated crop farming such as paddy rice, maize, potatoes, African eggplants, and other horticultural crops is the main economic activity in USB. During the wet season, maize, paddy, and potatoes are produced, taking advantage of increased irrigation water in rivers and from surface runoffs. This style makes USB extensively utilized and exploited throughout the year. Both

smallholder and large-scale farmers in USB do commercial farming, making crop farming very intensive (agricultural intensification), which are in two scenarios:

- (i) Agricultural intensification by an increased number of crops grown in the same piece of land within a year or per season. The availability of irrigation water channels has increased number of crops grown per plot per season. The frequency has increased from once per season or year up to six croppings per year in the same plot in some parts of USB, i.e., Igalako, Mubuyuni, Uturo, Ihahi, and Kapunga. This provides more income to farmers and further accelerates farm expansion and urbanization in the area. On the other hand, this provides no chance for soil recovery, posing soil health degradation threatening land productivity and sustainability. Agricultural expansion without intensification of required agro-inputs, e.g. more land is being used for production while the actual yield per area remains the same or even declines because of the poor land quality. This is observed in many parts of Tanzania (Malley *et al.*, 2016).
- (ii) The second scenario of agricultural intensification in USB involves high mechanization and agrochemicals uses. The difference between farmers in Usangu and other parts in nearby areas such as Madibira, Idodi, Ilembula, etc., is that farmers in USB have highly invested in farming machinery. For example, no or very few farmers use oxen or hand hoe to plough their paddy fields; all use a power tiller tractor (two-wheeled tractor) or four-wheel drive tractors. It is estimated that USB has more than 60 power tiller tractors and 40 four-wheeled-drive tractors operating during land preparation season (Mbule personal communication, 2021). Furthermore, other farmers opened up firms for hiring or providing farm machinery services due to increased machinery services demand for land preparation, planting (e.g., in Kapunga), and harvesting. This intensified agriculture in USB, leaving less room for traditional practices. High mechanization has driven the farming system from mixed cropping to monoculture farming, where only one crop is grown at a time for easy mechanization. Although it is efficient, it poses a challenge as it does not promote crop diversity, thus affecting soil health, soil fertility, productivity, and sustainability. To achieve business-oriented farming, farmers in USB have extensively invested in agrochemicals use, i.e., fertilizer, pesticides, herbicides, and growth promotors. Fertilizer use has increased significantly in the last 20 years for most farmers. The number or amount of fertilizer used per unit area has increased

exponentially, on average from 263 000 metric tons (mt) in 2010 to 574 000 mt in 2020 (Ariga & Heffernan, 2012; Valev, 2012). For instance, the use of nitrogenous fertilizer (Urea) in paddy farming at Kapunga has risen from 2 bags or 100 kg of Urea per hectare to about 5 bags or 250 kg of Urea per hectare (Kitambi personal communication, 2022). At the same time, pesticide application frequency increased from 2 to 8 times per cropping season; herbicide application has been adopted as a sole weed management practice from planting to harvesting (Matowo *et al.*, 2020; Philbert *et al.*, 2019). Also, the use of plant growth promoters has been observed to increase, especially in potato farming (Kimaro, 2019). All these are conducted to boost and achieve higher yields per unit area which have been reported to be unachievable under traditional standard agronomic practices. This might be associated with uncharacterized soil health and quality decline in the agro-ecosystem. Although increased use of agrochemicals boosts yields (Matowo *et al.*, 2020), economists suggest that the profit margin has been highly reduced due to increased production costs and reduced land productivity profitability, ecosystem health, water quality and biodiversity. Therefore, despite the positive impacts of increased use of agrochemicals on farmers' economies, it is likely to compromise agro-ecosystem productivity and quality through soil and water contamination and pollution.

Currently, there is a lack of studies on characterization of the influence of current land use and its intensification in soil and water quality in Usangu agro-ecosystem. Thus, there is a need to characterize soil health and quality, soil and water contamination and pollution status in the area; to estimate environmental and ecological health risks associated using contamination indexes. Furthermore, to estimate the bio-accumulation and translocation of PTEs in plant materials grown in Usangu basin. Following increased agrochemicals use, especially fertilizers, there is a need to test the soil nutrients status (P as typically the major limiting nutrient (Panagos *et al.*, 2022)), dynamics and interaction to understand its holding capacity, saturation, sorption and desorption capacity, behavioural reactions to added plant nutrients; and their influence to soil invertebrate (earthworm) distribution and diversity as an agro-environmental indicator. All this information is currently missing in Usangu agro-ecosystem.

Soil degradation and environmental challenges: Under the current urbanization, population increase, agriculture expansion and intensification, it is evident that there are noticeable soil degradation and environmental challenges existing in Usangu basin (Malley *et al.*, 2007). This includes soil fertility, soil health degradation, and contamination of soil, plants, and water resources. Although these challenges might have a considerable effect on the productivity and sustainability of Usangu agro-ecosystem socially, politically, economically and environmentally, no studies have been conducted to study in detail and document these challenges and propose potential and possible remedies.

Currently, in many agro-ecosystem, including Usangu, monocropping is a dominant farming practice, which resulted in increased agrochemicals dependency such as fertilizer, herbicides, and pesticides, these practices are potentially unsustainable because can lead to soil fertility decline and environmental contamination by toxic elements (Bationo *et al.*, 2005). Consequently, smallholder farmers hardly get higher crop yields due to declining soil nutrients and limited access to agrochemicals such as mineral fertilizer. Therefore, comprehensive soil fertility monitoring and management is vital to achieve higher land productivity and sustainably managing the available arable land. There is an uncertainty on the crop production sustainability in Usangu agro-ecosystem (UA) due to increasing soil fertility decline and increasing PTEs (As, Cu, Cd, Mn, Pb, Ni, Cr, etc.) accumulation in agricultural soils as impurities from agrochemicals which are known to reduce fertilizer responses to plants by reducing plant nutrient (Zn, Ca, P, and N) availability (Lema & Mseli, 2017). Over the years, UA has experienced a widespread soil fertility decline due to continuously intensive cropping (Mowo *et al.*, 1993; Senkoro *et al.*, 2017), where lower paddy rice productivity (<2.1 tons/ha) versus 6.6 tons/ha an average production potential in the area has been reported. Thus, characterizing soil nutrient status in UA is vital as it will help estimate and predict land productivity and sustainability and enable setting out best management practices for increased crop production. Currently, characterization and assessment of soil fertility status in Tanzanian agro-ecosystems are confined to few areas due to limited access to soil science laboratories and high consultation and analytical costs. The lack of data from soil testing laboratories and published literature in UA and other agricultural lands in Tanzania has limited soil fertility management plans required to ensure high crop productivity and sustainability. Hence, the present study analyzed and characterized soil fertility status in different irrigation schemes in UA to fill gaps in understanding to support the development of sustainable soil management plans.

In agriculture productivity, phosphorus (P) is a vital macronutrient essential for better plant root growth and fruit formation and is the most limiting plant nutrient sourced from non-renewable materials (Balmford *et al.*, 2012; Busman *et al.*, 2009; Panagos *et al.*, 2022). In highly weathered tropical soils, phosphate ( $\text{PO}_4^{3-}$ ) is less available to plants due to high sorption and fixation processes driven by high sesquioxide concentration (i.e., oxide of aluminium or iron) and clay content. Therefore,  $\text{PO}_4^{3-}$  availability in soils from fertilizer added in the form of diammonium phosphate (DAP), NPK, triple superphosphate (TSP), and single super phosphate (SSP) is determined by sesquioxides, soil pH, and clay content (Sato, 2003). On the other hand, secondary soil improvement can positively influence or promote the bioavailability of P in agricultural soils. For example, organic fertilizers and mulching increase the bioavailability of P in tropical soils by providing organic matter (OM) that creates coating for Al and Fe bindings and changing the redox situation in the soil. High sesquioxides and clay content reduces P available for plant uptake, including paddy rice (Bachmann *et al.*, 2016; Guppy *et al.*, 2005; Jalali, 2017), resulting in stunted growth and low yields for resource-poor farmers. Whilst farmers with sufficient capital increase the application rate for inorganic phosphate fertilizers (up to 120 kg/ha) to compensate for the amount of fixed P in the soil (Renneson *et al.*, 2016), this can lead to P build-up in soils exceeding soil capacity to hold excess P (critical levels), resulting in high risks of P loss from agricultural fields to surface and groundwater through leaching, surface runoff and soil erosion, leading to eutrophication of water bodies (Moss, 2008; Sharpley, 2015).

The P added from organic and inorganic fertilizer in agricultural soils its availability to plants is usually determined by different factors such as capacity of the soil to adsorb P (PSC) and making it available for plant uptake when needed, soil pH, and metal cations (Barrow *et al.*, 2021). Furthermore, the availability of P for plant uptake from agricultural soils is determined by P saturation degree (PSD) of the soil; PSD determines the additional amount of P the soil can be ready to take up and hold it safely without causing significant P loss to the environment (De Bolle, 2013). The capacity of the soil to hold P added from fertilizer and other materials rich in plant nutrients is determined by PSC, and PSC estimates the amount of P which can be available for agricultural uptakes, runoffs, and leachetes (Schoumans & Chardon, 2014). In contrast, PSD determines and estimates the amount of P fixed in soil and additional soil capacity to hold P to a certain soil depth (De Smet *et al.*, 1996). To raise fertilizer use efficiency and lower P loss to environment, it is scientifically advisable to include PSC and PSD in fertilizer requirements

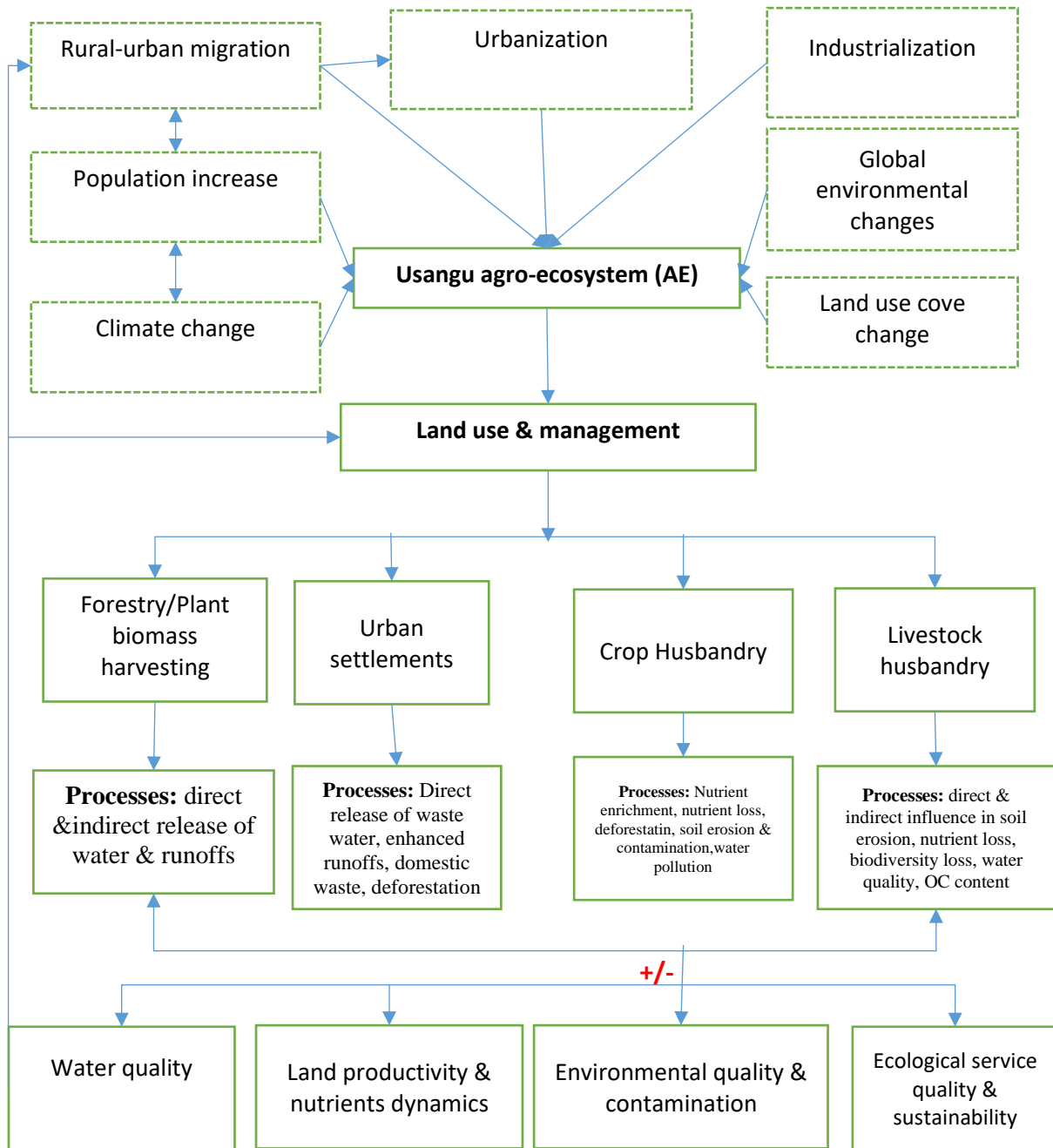
planning, estimation, and recommendations (Schoumans, 2015). Both PSC and PSD can be used as P management criteria in agricultural soils and as environmental quality indicators in estimating the risk of P loss from agricultural fields (Uriyo *et al.*, 1977). Therefore, sustainable P management in soils is influenced by inherent P status, PSC, PSD, pH, and clay content (Ngatia & Taylor, 2018; Schoumans & Chardon, 2014; Sharpley, 2015). PSC and PSD determine the amount of nutrients (N and P) available for plants, leaching, and surface runoffs to watercourses (De Bolle, 2013). In addition, these parameters are important to predict the relationship between P fertilizer use and eutrophication of water bodies and impacts on soil and water quality (Sharpley & Mcdowell, 2016). For that reason, it is vital to assess current soil P status, sorption capacity, and saturation in different land uses within paddy wetlands areas and their vicinity. This will allow development of site-specific P management strategies to ensure maximum yields and reduced P loss to water bodies. Despite the importance of PSC and PSD, they had never been established or estimated and studied in agricultural soils of Usangu agro-ecosystem and Tanzania in general.

Since 1985 Usangu agro-ecosystem experienced high use of agrochemicals such as herbicides, pesticides, and fertilizer; as pointed out earlier (Machibya & Mdemu, 2005), the practices may pose a huge environmental challenge in agro-ecosystem (AE) as a result of higher PTEs in soil, water, and plants tissues (Goncalves *et al.*, 2014; Teng *et al.*, 2010). Hence, assessment of PTEs accumulation in agricultural soils in UA is important for AE quality monitoring and management. This is important because contemporary data on PTEs accumulation, distribution, bioconcentration (BCF), and translocation factors (TF) in many AE in Tanzania is a serious knowledge gap (Simon *et al.*, 2016), thus, limiting strategic planning for PTEs management. Based on this rationale with respect to PTEs in agricultural soils, this study addressed: (a) PTEs spatial distribution in agricultural soils (topsoils 0-30 cm) across UA; (b) comparison of total PTEs and bioavailable PTEs determined to national and international published maximum permissible limits in agriculture and natural habitats; (c) variation of PTEs concentration in topsoils from predominantly agriculture areas and mixed residential and agricultural areas; (d) influence of land use (conserved, paddy farming and maize farming areas) on PTEs accumulation and distribution, (e) bioconcentration (BCF) and translocation factor (TF) of PTEs from agricultural soils to paddy rice plants.

Therefore, the research scope and thesis aimed to address the following aspects using Usangu agro-ecosystem (UA) as a case study.

- (i) The current soil nutrients status (especially P and N) and their availability in Usangu basin. This helps outline the potential UA weakness, which might affect its productivity and set out baseline information for nutrient management because the available information is scant and outdated (more than 30 years old).
- (ii) The soil capacity to hold P, its saturation degree and interaction of P added to the soil (sorption and desorption). This information is important in planning the amount and fertilization program in agricultural fields and provides data to estimate nutrients loss risk (e.g., P loss to environment from agricultural fields).
- (iii) The water quality and eutrophication using chemical properties such as P, N, pH and PTEs concentrations to provide a key insight into how agriculture activities influence water resources quality and connected ecosystems.
- (iv) The PTEs accumulation, distribution, bioconcentration (BCF) and translocation factors (TF), and pollution risk in agricultural soils, water, and plants. This is conducted because the commonly used agrochemicals in UA are reported to be associated with PTEs impurities, and runoff from urban areas used as irrigation water in UA is likely to have elevated levels of nutrients and PTEs, which can bioconcentrate from agricultural soils into plants and soil invertebrates leading to environmental and health risks.
- (v) The soil quality and earthworm abundance and diversity in agricultural soils of UA to understand and document the influence of current farming activities on soil quality and soil invertebrate abundance and diversity.

This study has used the newly collected research data to propose potential remedies associated with practice and policy recommendations that, when adopted and implemented, will increase land productivity and improve environmental quality. The schematic summary of factors governing agro-ecosystem functioning (dotted box), the land use and management, and processes happening in each land use (author's conceptualization) which is the focus of this thesis, is shown in Fig. 2.



**Figure 2: The schematic summary of factors governing agro-ecosystem functioning (dotted box), the land use and management, and processes happening in each land use (authors' conceptualization). The (+) and (-) signs indicate positive or negative influences of an activity or process on agro-ecosystem, land use and their associated management. This flow is the focus of this thesis**

## 1.2. Statement of the problem

Over the last 20 years, paddy farming in Usangu basin has dramatically increased, with higher use of pesticides, herbicides and synthetic fertilizer (N and P) (Ngailo *et al.*, 2016). Despite the increased use of synthetic fertilizer (N and P), low yields (<2.1 tons/ha) for paddy rice, maize, potatoes, and other crops have been observed in the basin compared to yield potential (>6.5 tons/ha) (Katambara *et al.*, 2016). Low yields may be due to low N and P because of poor fertilizer application methods, fertilizer mismanagement (broadcasting in flooded fields) and soil P fixation and loss (Malley *et al.*, 2007, 2017). Higher use of agrochemicals in the basin potentially causes soil and freshwater contamination. The loss of N and P to water bodies from agricultural fields reduces plant-available N and P and can lead to PTEs contaminations, as reported by Forestry and Beekeeping Division (2007). Historically, the PTEs concentration in water in farming areas in USB was reported to be higher in water runoffs (FBD, 2007). However, the concentration of PTEs and other inorganic nutrients in the Kimani river was near background as they were unaffected by anthropogenic activities. High amounts of inorganic nutrients and PTEs suggest that Usangu basin quality was altered by anthropogenic activities (Fox, 2004).

The role of environmental factors, such as total P, N, and PTEs accumulation in soils and eutrophication, remains poorly understood in Southern Highlands Tanzania (SHT). Where previous studies conducted were limited in scope, often only concerned with water chemistry in rivers and ponds in non-agricultural regions. Mshana (2015) and Fanny (2019) found serious water quality degradation in the SHT basins, which was linked to agricultural effluents from farming areas. In addition, loss of N and P to environment may impact abundance, diversity, and soil invertebrates (earthworms) which are important in soil fertility (Wang *et al.*, 2018). Thus, there is a need to understand the influence of P fertilization on soil invertebrate communities, soil and water quality, PTEs accumulation and distribution. This will allow monitoring, management and development of mitigation strategies for soil fertility decline, PTEs accumulation, and eutrophication of reservoirs in SHT. The PSC, PSD and other P related indicators are required for P management and to estimate the risk of P loss from agricultural fields but have never been studied in SHT. Therefore, this study characterized in detail soil nutrient (N and P) dynamics, availability, P sorption and saturation, PTEs accumulation, distribution and pollution risk in

different land uses, water quality and eutrophications; in addition, assessed earthworms abundance and diversity in agricultural soils.

### **1.3. The rationale of the study**

The availability of high plant nutrients and quality water are important to achieve anticipated land productivity, economic and environmental demands amid the growing population, expanding irrigated agriculture, and changing climate. However, sustainable and efficient utilization of available water resources and plant nutrients in UA requires careful planning and management strategies. These plans and strategies must be guided by a solid understanding of soil fertility status, plant nutrient dynamics, P sorption and desorption capacity and acceptable PTEs levels in agricultural soils, plants, and water, and factors guiding them. This study characterizes current P and soil fertility status and their availability in three land-use (conservation areas, paddy and maize farming areas), P bioavailability, PSC, PSD, P sorption and desorption, potential nutrients loss to water bodies and PTEs accumulation in soil, water and plants in UA. Furthermore, pollution and contamination indexes in soil and water were computed based on the study data, and contamination and pollution classes were developed in all studied areas, which were never done before.

Furthermore, to estimate PTEs availability in plant tissues, especially paddy rice, bioconcentration (BCF) and translocation factors (TF) were computed; this enables estimation of paddy rice grain quality and possible health risks. Furthermore, the study assessed abundance, diversity, species richness and evenness of earthworms as an agro-ecosystem engineer in agricultural soils in all irrigation schemes in UA. This helps to determine the influence of current farming practices on agricultural soil health and soil invertebrates (earthworms) biodiversity, which can affect nutrient recycling.

### **1.4. Research objectives**

#### **1.4.1. General objective**

Assessment of soil phosphate status, sorption, saturation dynamics, water eutrophication and PTEs accumulation in UA to estimate environmental quality impacts linked to current land use and propose potential management strategies for improved land productivity, environmental quality, and sustainability.

#### **1.4.2. Specific objectives**

- (i) To determine current soil fertility status in UA.
- (ii) To establish soil phosphate sorption capacity (PSC) and phosphate saturation degree (PSD) indicators as an estimate for P fixation and desorption risk.
- (iii) To compare soil quality in different paddy farming areas.
- (iv) To evaluate PTEs accumulation and pollution risks in soils and plants.
- (v) To assess surface water quality in Usangu agro-ecosystem.

#### **1.5. Research questions**

To accomplish this study, the following research questions were addressed and used as a guideline

- (i) What is the current soil fertility status in UA?
- (ii) What are PSC, PSD and risk of P loss to water sources in UA soils?
- (iii) What is the soil quality of different paddy farming areas in UA?
- (iv) What is the extent of PTEs accumulations and pollution risk in soils and plants in UA?
- (v) What is the surface water quality in UA?

#### **1.6. Significance of the study**

This study intended to significantly impact sustainable land productivity, environmental quality, and sustainability of UA to ensure increased land productivity, food security, and environmental quality. Here are some of the knowledge gaps addressed, which signifies the importance of this study:

- (i) The PSC and PSD characterization in agricultural soils from UA have revealed soil capacity to sorb P and allow its availability to plant uptake, but also the PSD help to reveal the P saturation status of agricultural soils in Usangu, where studied areas were observed to have P unsaturated status; however, some sites observed to have PSD closer to saturated status, thus if the trend continues at the same pace saturated status will be reached soon in identified sites accelerating P loss and water contamination. The batch sorption-desorption experiment conducted in agricultural soils from Usangu agro-ecosystem revealed that continuous application of P to 5 mg/L (100 kg/ha) may

accelerate P loss to the environment, thus reducing the P-fertilizer use efficiency and leading to water contamination in the area. All these information were missing in Usangu agro-ecosystem and other agro-ecosystem in Tanzania; thus, this study provides baseline data and information which will be used for further studies on P management and eutrophication control.

- (ii) The PTEs characterization and quantification in agricultural soils and plants in Usangu agro-ecosystem have never been carried out by previous researchers or none attempted. Thus, current study quantified and characterized PTEs accumulation among irrigation schemes and land use (conservation areas, maize and paddy farming areas), where total PTEs, bioavailable PTEs, and pollution indexes in soils and plants characterized and revealed that some PTEs were above acceptable limits indicating contamination and pollution risks and it was found that highly intensified irrigation schemes had higher PTEs concentration than non-intensified schemes. But also, this study revealed that farming areas (maize and paddy farming areas) are associated with higher PTEs concentration in the landscape than conservation areas. Furthermore, it was observed that paddy rice plants from Usangu agro-ecosystem had BCF of greater than 1 for some studied PTEs, but also the TF (Translocation factor) of PTEs in paddy rice plants in Usangu agro-ecosystem revealed that more PTEs accumulated in below-ground biomass (roots) than above-ground biomass (straws and grains), indicating that above-ground biomass such as grains is associated with less PTEs health risks. All these informations were missing in Usangu agro-ecosystem and other agro-ecosystem in Tanzania; thus the current study provide baseline information for further management studies.
- (iii) Furthermore, the current study computed the pollution indexes for PTEs in Usangu agro-ecosystem soils where computed indexes were based on total PTEs among land use and irrigation schemes such as adverse effect index (AEI), geochemical accumulation index (Igeo), contamination factor (CF), pollution load index (PLI), enrichment factor (EF), potential ecological risk index ( $E_r^i$ ) and comprehensive risk index (RI), where these indexes have not yet been computed and studied in agricultural soils in Usangu agro-ecosystem (UA). Based on the computed indexes, the current

status of UA observed to be associated with PTEs adverse effects due to exceedance of SQG values, minimal PTEs geochemical accumulation in agricultural soils, and PTEs potential ecological risks determined. The computed indexes serve as baseline information required for further PTEs monitoring in agricultural soils in UA to ensure environmental quality and sustainability.

- (iv) The water quality and eutrophication in Usangu agro-ecosystem have been characterized and covered all major (10) irrigation schemes, and none attempted it before. Water quality was analyzed in intakes, irrigation channels, paddy fields, and drainages from paddy fields, where PTEs and plant nutrients concentration were determined and observed to increase as water moves along paddy fields. In the current study, the concentration of N and P observed to be higher than established limits in drainages draining from agricultural fields, thus presenting water quality degradation and water resources eutrophication risks. Furthermore, the study found that irrigation water used in UA is associated with some crop production, animal and human use limitations due to water quality degradations.
- (v) The present study provide useful results and data that can be utilized for agro-ecosystem management in other areas of tanzania and the world with similar climatic condition and management practices as Usangu agro-ecosystem to improve land productivity, environmental quality and sustainability.

## **1.7. Delineation of the study**

This dissertation is written in a monograph format constituted into five chapters: introduction, literature review, materials and methods, results and discussion, and conclusion and recommendation. The content of each chapter is outlined as follows;

Chapter 1 provide the general introduction of the research where the background information on the study area, soil fertility, P sorption capacity and saturation, sorption and desorption dynamics, water quality and PTEs accumulation (in soils, plants and water), distribution and pollution risks in UA is presented. The chapter further outlines statement of the problem, rationale of the study, research objectives, research question, significance of the study and delineation of the study.

Chapter 2 presents the literature review related to the research topic to develop a background of this dissertation for a wider audience, the component discussed in this chapter include soil phosphate sorption capacity (PSC), phosphate saturation degree (PSD) and P loss to the environment, PSC and PSD in Sub Saharan Africa soils and land productivity, nutrient loss and water eutrophication, potential drivers for P loss and water eutrophication, PTEs accumulation, distribution, and pollution risks in agricultural soils and water, the influence of paddy farming on soil quality, farming systems in East Africa AE, PTEs sources in AE, soil and water PTEs exposure pathways, current drivers for increased PTEs in East Africa AE, and PTEs bioavailability and distribution in East African AE.

Chapter 3 presents different international standards and adapted methods used to analyze various parameters of this study. This includes methods and materials used to characterize all objectives of this study but also describes in detail the study area and applied standard operating procedures (SOP) for various methods.

Chapter 4 presents results obtained by applying various standard methods as described in chapter three; results are presented in tables, figures and maps and where possible, results are presented in equations and symbols. Later in the chapter, the discussion of the generated results is conducted to provide interpretations and the key message intended for the audience. This chapter also compares the obtained results with results from previous studies in the study area and other parts of the world with closely similar agro-environmental conditions to gain a wide audience and

perspectives. Finally, Chapter 5 provides a general conclusion, synthesis, and recommendation based on the research results and discussion. The recommendation is divided into recommendation to scientific community, recommendation to policymakers and recommendation to farmers and other local land users in the area. In addition, the scientific contributions of this study is presented at the end of this chapter. But also the author (Marco Mng'ong'o) declares that this thesis includes contents that have been published (research papers and review) from this research work by the author Marco Mng'ong'o and Co-authors (Supervisors, i.e., Prof. Patrick A. Ndakidemi, Prof. Linus K. Munishi, Prof. Sean Comber, and Prof. Thomas H. Hutchinson) before submission of this thesis as a requirement for graduation as they appear at the end of this document as research output.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1. Background on phosphorus

Phosphorus (P) is a vital macronutrient required for growth and development of plants and animals (Némery & Garnier, 2016). It is a constituent of nucleic acids, and it is important in biological energy transfer processes which are vital for life and growth (Schoumans *et al.*, 2014). In an ecosystem, P has two issues (P paradox): low P leads to poor plant growth and limited yields. In contrast, high P content in the ecosystem interferes with environmental quality through eutrophication and soil acidification (Ngatia *et al.*, 2019). P is often available in the soil in a lower amount than plants requirement for optimal plant growth due to P adsorption to Ca, Fe, Al and clay minerals. But also because of the relative slow P release from mineral weathering. The P limitation in ecosystems is one of the main structuring elements in natural ecosystems through competition wherein the differences in P availability between soils promote biodiversity. Eutrophication removes this limitation leading to some plants or algal types to take over the entire ecosystem and reducing biodiversity. To promote soil nutrient status, organic and synthetic P fertilizers have to be added (Chintala *et al.*, 2014). Where P can be added to soil in forms of inorganic fertilizers such as triple superphosphate (TSP), NPK, diammonium phosphate (DAP), and single super phosphate (SSP) or can be added from organic manures such as pig slurry and poultry manure which often contain different levels plant nutrients. However, an excessive P application can cause P buildup and saturation (Borda *et al.*, 2014; Smith & Schindler, 2009). The P saturation in agricultural soils will leave more P in soil solution, which will be readily available to plants but also can easily be lost to watercourses through leaching, soil erosion and surface runoffs affecting plant-available P, water quality and biodiversity (Ngatia & Taylor, 2018; Yang *et al.*, 2008).

The existence of P in soils is in three orthophosphates (O-P) forms ( $\text{H}_2\text{PO}_3^-$ ,  $\text{HPO}_4^{2-}$  and  $\text{PO}_4^{3-}$ ) depending on soil pH (Sato, 2003). The O-P can combine with cations, i.e.  $\text{H}^+$ ,  $\text{K}^+$ ,  $\text{NH}_4^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$ , and  $\text{Fe}^{3+}$  in the soils; hence its availability to plants becomes reduced. Therefore, in the soil, P is subjected to dynamic internal cycling, which involves P moving from primary minerals into

secondary minerals that are soluble in soil solution. The dissolved P from primary minerals and fertilizers can bind to metal cations, i.e.,  $\text{Ca}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Al}^{3+}$  and  $\text{K}^+$  to form secondary P minerals depending on the soil pH. For instance, in acidic soils, P bind to as Al-P and Fe-P and in alkaline soils, P precipitate as Ca-P (Sato, 2003); all these forms are less readily available for plant uptake. Dissolved P can also be transformed by plants and micro-organisms into organic P forms such as adenosine triphosphate (ATP), adenosine diphosphate (ADP) and deoxyribonucleic acid (DNA) or lost to water bodies via leaching and runoffs (Bortoluzzi *et al.*, 2015; Fink *et al.*, 2016).

## 2.2. Soil phosphate sorption capacity (PSC)

The PSC of the soil is the capability of the soil to bind P applied to it (e.g. as fertilizer), thus making it available to plants later in the growing season and preventing it from leaching or erosion (Schoumans, 2015). In addition, soils with higher PSC can retain applied P more strongly, so it is not immediately released for plant uptake or leaching than soils with a low PSC (Sharpley *et al.*, 2001). There is thus an optimum PSC wherein to low PSC the P is quickly leached and too high PSC the P is bound so strong it is not available and this value varies from place to place depending on soil chemistry but the value is usually 75% of the summation of the determined Al, Fe and Ca will allow P availability for better plant growth. The soil PSC is determined by soil chemistry, texture, acidity and soil organic carbon, and concentrations of metal cations; the capacity of the soil to hold P can be computed with soil P sorption model (Equation 1) as described by De Bolle (2013).

$$\text{Soil P sorption capacity (PSC)} = \alpha(\text{Fe}_{ox} + \text{Al}_{ox} + \text{Ca}_{ox}) \quad (1)$$

Where “ $\text{Fe}_{ox}$ ,  $\text{Al}_{ox}$ , and  $\text{Ca}_{ox}$  = ammonium-oxalate-oxalic acid extractable Fe, Al, and Ca (in mmol/kg) respectively, PSC = P sorption capacity (in mmol/kg),  $\alpha = 0.5$  capacity of the ammonium-oxalate-extractable oxides to bind P (50%)” (Freese *et al.*, 1992).

For better predictions of P availability to plants and loss to surface runoff, it is crucial to create estimates of soil PSC in the study area (Borggaard *et al.*, 2004) by measuring soil Fe, Ca, Al (hydr) oxide and clay content. The PSC strongly correlates with P adsorbents (Fe, Al, and Ca (hydr) oxides) in the soils. Therefore, by determining P adsorbents concentration, the capacity of the soil to bind P can be estimated. Furthermore, the acidic ammonium oxalate extractable Fe and Al estimates the amount of non-crystalline Fe and Al levels in soil minerals, indicating the summation

of the adsorption sites that can be available for P adsorption, especially in non-calcareous soils (Guppy *et al.*, 2005). Thus, agricultural soils with optimum PSC have the capability to hold more P firmly, and less P is lost to the environment; consequently, soils with optimum PSC have higher plant-available P, and better plant growth is expected; however, in some scenarios like in highly weathered tropical soils, high or extreme PSC affects P available for crop plant uptake since all added P is sorbed strongly to soil colloids making it less available for plant uptake.

On the other hand, agricultural soil associated with low PSC is characterized by high P in soil solution, and more P is available to be lost to the environment through leaching, surface water runoff, and soil erosion. However, most soils in Tanzania and Sub-Saharan Africa, their PSC have never been characterized, leaving the knowledge gap for management options because PSC is essential in planning nutrient augmentation programs as it helps to indicate whether single or split fertilizer application will be required. Therefore, there is a need to assess PSC in agricultural soils in agro-ecosystem to create and ground truth PSC and its connection amongst soils attributes and soil mediated P loss potential in agro-ecosystem, especially in paddy farming areas, for awareness-raising on the potential risks to water quality and to strategize P management based on PSC.

### **2.3. Phosphate saturation degree (PSD) and P loss to the environment**

The PSD is an indicator showing the overall P accumulated in the soil compared with the capacity of the soil to adsorb P (PSC) at a certain reference depth or up to the water table in soils with a shallow water table (De Smet *et al.*, 1996). The accumulation of adsorbed P higher than PSC increases P in soil solution so that P can be freely removed by plants or through surface runoffs and leachates (Sharpley *et al.*, 2001; Sharpley & McDowell, 2016). As is well described in section 2.2, in acidic soils, the main determinants of PSC are Al and Fe in their non-crystalline forms; hence, the measurement of PSD is determined by acidic ammonium oxalate extraction of amorphous aluminium and iron compounds in acidic soils and compared with inherent available P. The total PSD in the soil profile is calculated by considering the mean soil inherent P ( $P_{ox}$  P which is already available in the soil due to previous fertilizer application or organic matter mineralization) and mean PSC ( $Al_{ox}$ ,  $Ca_{ox}$ , and  $Fe_{ox}$ ) at a specified depth, such as 90 cm depth (Equation 2).

$$\text{Degree of P Saturation (PSD)} = \frac{P_{ox}}{\alpha(Fe_{ox} + Al_{ox} + Ca_{ox})} \times 100 \quad (2)$$

The determination and establishment of PSD help determine the concentration of P that will be easily lost from agricultural soils and threaten soil and environment quality (De Bolle, 2013; Schoumans & Chardon, 2014). In the soil profile, 0.1 mg/L is regarded as a lower boundary limit P concentration for eutrophication and the capacity of the soil to retain P in soil safely (P saturation) (De Bolle, 2013; Schoumans & Chardon, 2014). Thus, a soil with PSD of less than 24% in the whole soil profile is considered unsaturated as established by Dutch soil scientists in the Netherlands, but soils with PSD greater than 24% may accelerate loss of P to water bodies resulting in eutrophication and are termed to be saturated soils with respect to P (De Bolle, 2013; Schoumans & Chardon, 2014). Generally, PSD in different soils of different agro-ecosystem vary with inherent soil properties and has a strong correlation with P concentration in runoffs and drainages in water channels. However, the thorough literature search and available information on PSD characterization in Tanzanian soils are missing, as no or limited studies have tried to explore this factor. Therefore, it is important to study the PSD of agricultural soils of each area and include it as one of the criteria for P fertilizer requirement estimation, management, and eutrophication management.

#### **2.4. Phosphate sorption capacity and saturation in Sub-Saharan Africa soils**

Studies on P sorption and saturation and their impacts on environmental quality in soils and water have been conducted in Northern America and Europe (Van Den Bossche *et al.*, 2006). The use of a PSD critical values, which have been developed in other countries, is possible if where it will be applied has the same climatic condition and soil types as in the country of origin where that PSD value was developed or established since it is highly influenced by geology and climatic condition (Hongthanat, 2010). Despite the importance of PSD indicators in P management for agronomic use and environmental conservation, there are scanty studies on PSD and PSC in African soils. This leads to a lack of awareness and incorporation of PSD and PSC indicators in soil P management and water eutrophication mitigations (Ngatia *et al.*, 2019). Soil P management in most African soils is based on the assumption that P is always available at limited levels. However, recent studies by Sakané *et al.* (2011) on East African wetlands and irrigation schemes (URT, 2003) found many places in Usambara and Kilombero plains having soil bioavailable P of more than 46 mg/kg, an amount which is more than enough to cause accelerated leaching and runoff enriched with P to water bodies. Furthermore, algae blooms and excessive growth of other aquatic

plants have been observed in irrigation canals, rivers, dams and many African lakes, indicating higher enrichment of N and P from different sources such as agricultural fields (De Villiers, 2007). Thus, there is a need to evaluate soil P management perspectives in African agricultural fields, especially in wetland areas with a shallow water table and direct connection to water bodies, since this might exacerbate eutrophication (Sakané *et al.*, 2011). Due to the fact that no studies have established the P management critical levels for wetland agriculture, the detailed assessment of P status (PSC and PSD) and estimate of eutrophication risk in Tanzanian soils in paddy wetlands are important to ensure land productivity and sustainability.

## **2.5. Nutrient loss and water eutrophication**

Eutrophication refers to nutrient (N and P) enrichment in water bodies, characterized by excessive growth of aquatic plants and algae, potentially leading to oxygen depletion and ultimately production of a layer of detritus on water surfaces, inhibiting light penetration and re-oxygenation of water (Khan & Ansari, 2005). Fish production may also be impacted through oxygen deficiency and algae toxins produced by some blue-green algae, where in Tanzania toxic algal blooms are also linked to mass deaths of flamingos (in Lake Manyara and Lake Momella). Farming practices and biogeochemical soil characteristics greatly influence P loss and water eutrophication in both cultivated and non-cultivated areas (Balmford *et al.*, 2012).

Higher use of P-fertilizer in paddy farming for basal and top dressing associated with fertilizer mismanagement (continuous flooding of fields and application in a single application) reduces plant-available P and increases the risk of P loss to water bodies resulting in eutrophication and contamination with PTEs such as Cd and Pb, which are common impurities in P-fertilizers and other agrochemicals (Margenot *et al.*, 2016; Ngailo *et al.*, 2016). The current fertilizer application practices used in UA may accelerate water eutrophication; farmers apply fertilizer on flooded fields, or flooding is conducted a few days after fertilizer application; furthermore, most paddy fields use flooding system of irrigation which enhance P losses due to constant in and out water movement in paddy fields but also due to enhanced P release from soil column due to anoxic conditions (changing redox) (Yang *et al.*, 2018). These practices have a negative environmental impact as they enhance P loss via leaching and runoff to water bodies.

Despite the fact that N and P have significant role in water eutrophication in freshwater resources, it is agreed by number of scientists that the role of P in freshwater resources is higher than that of N, while N is more dominant in marine ecosystem. But generally, the availability of both N and P worsen more the situation than availability of either N or P alone (Camargo & Alonso, 2006). For that reason, understanding and determining PSC, PSD, and other related parameters are key in understanding eutrophication of freshwater ecosystems because the named parameters determine P available for plants and P for surfaces water runoffs because P is a sole nutrient mainly responsible for eutrophication in freshwater ecosystems. Furthermore, as water moves along the paddy fields, their quality changes as it accumulates nutrients and metals lost from agricultural areas to other water reservoirs; thus, drainages from these fields can act as potential nutrients and metals inputs to aquatic ecosystem in the vicinity. Therefore, assessing water quality and nutrient composition in irrigation water and drainages in AE in USB is critical for better understanding and determining necessary management strategies required to achieve long-term land productivity and environmental quality.

On the other hand, agricultural intensification with increased use of agrochemicals in UA, as mentioned earlier, can potentially increase the concentration of undesired chemicals/elements such as potentially toxic elements (PTEs) in agricultural soils, thus affecting agro-ecosystem quality. Higher PTEs concentrations may cause toxic effects in plants, soil invertebrates and microbes, leading to reduction in soil biodiversity and soil fertility. Furthermore, PTEs in soils can affect animals and humans via food and water intake or ingestion of contaminated soils. Some of the PTEs commonly reported to affect soil quality in many agro-ecosystem include iron (Fe), lead (Pb), copper (Cu), arsenic (As), mercury (Hg), cobalt (Co), silver (Ag), nickel (Ni), selenium (Se), chromium (Cr), zinc (Zn), manganese (Mn), and cadmium (Cd) (Qin *et al.*, 2021; Renu *et al.*, 2021). The environmental quality regulatory authorities consider PTEs as key environmental contaminants; thus, their concentration has to be controlled and kept low as much as possible to avoid associated environmental health risks and soil pollution (Heidari *et al.*, 2021). Furthermore, the accumulation of PTEs in agricultural soils can increase its levels in plant tissues leading to health risks to animals and humans when consumed, thus elevating its level in the human body via food intake leading to health risk (Paithankar *et al.*, 2021; Phuong *et al.*, 2008, 2010).

Higher N, P and eutrophication can be easily noticed by excessive growth of algae and other aquatic plants in water bodies (De Villiers, 2007; Fox, 2004; Khan & Ansari, 2005; Moss, 2008; Schindler, 2006; Sharpley & McDowell, 2016). Owing to the fact that point source pollution has been controlled in many parts of the world (Not in Sub-Saharan Africa) to water bodies, agricultural fields have become the important diffuse (non-point) source of nutrients (N and P) to water bodies through leaching, drainages, and surface runoffs. In irrigated paddy farms of SHT, irrigation water is taken from river catchments or rivers flowing through Ihefu and Usangu plains like river Lukosi, Little Ruaha, Kisigo, Mbarali, Chimala, Ipatagwa, and Mswiswi (Mtahiko *et al.*, 2006). Once the water is used in paddy fields, users must return at least 20% of the water used in irrigation to the primary source river to enrich the Great Ruaha River (GRR). The returned water is highly contaminated with agrochemicals, fertilizers and their impurities, including PTEs (Victor & Francis, 2013). The concentration of N and P in water effluents draining from paddy fields of SHT is unknown but might be higher than normal ( $>0.1$  mg/L) (Fox, 2004). This can be evidenced by the vigorous growth of algae blooms and other aquatic plants in water bodies and irrigation channels as a result of increased P and N enrichment from paddy farms (Kashaigili *et al.*, 2006). This has negative impacts on aquatic life and other downstream water users such as humans, wildlife, fish and soil invertebrates (Fox, 2004; URT, 2003). Therefore, prevention and protection actions based on sound evidence are required to safeguard the surface water quality in agricultural systems and in the vicinity; this is possible through characterization of water qualities in agro-ecosystem and connected ecosystems.

## **2.6. Potentially toxic element (PTEs) accumulation in soils and water**

Generally, PTEs are elements that can be toxic to plants, animals and soil invertebrates, especially when available in extreme amounts. Some notable examples of PTEs, including Hg, Cd, As, Pb, and Cr, are biologically non-essential elements and are highly toxic to humans, animals, and plants (Qin *et al.*, 2021). On the other hand, some PTEs (Zn, Fe, Co, Cu, Se, and Mn) are plant micronutrients, especially at lower concentrations but may become environmental contaminants of concern if they occur in unusual higher concentrations. Soils also contain naturally occurring PTEs such as Cr, Cd, As, Ni, Cu, Hg, Zn, and Pb (Wei & Yang, 2010), but they are available in small quantities. The disproportionate agrochemical uses (such as herbicides, pesticides and fertilizer) in agricultural fields have been reported to exacerbate PTEs concentration in agricultural

soils (Ballabio *et al.*, 2018; Khani *et al.*, 2017; Ngoc *et al.*, 2021; Nkinda *et al.*, 2020; Nriagu, 1992). Generally, PTEs (Pb, Cr, Hg, and Cd) are considered life-threatening pollutants by monitoring authorities due to their toxicity and bioaccumulation potential in the environment. The inorganic P fertilizer is made up from different rock phosphates, which have an appreciable amount of other elements such as Cd, Cr, and Pb, which can accumulate in soils (Khani *et al.*, 2017; Wei & Yang, 2010). In agricultural fields, inorganic P fertilizers are the primary source of PTEs contaminants, as it has traces of Cd, Pb, As, and Cr (Chibuiké & Obiora, 2014; Khani *et al.*, 2017). From P fertilizer, the PTEs may enter the food chain through soils, plants, water, and other PTEs such as Cu also enter the soil through fungicide, herbicide and pesticide use. Change in redox concentration through agricultural practices (drainage or submergion) may also mobilize natural metals (Wei & Yang, 2010; Xu *et al.*, 2017). However, many plant species can tolerate several PTEs, such as Fe, Mn, Cu and Zn, in small amounts; indeed they are essential elements at appropriate concentrations. In contrast, other PTEs such as Pb, Hg, Cd, and As are never beneficial and are considered toxic ('poisonous') to both plants and animals (Chibuiké & Obiora, 2014). Higher concentrations of PTEs can directly affect plants through disruption of cytoplasmic enzymes and cell structures due to oxidative stress (Chibuiké & Obiora, 2014; Hussain *et al.*, 2017). Indirectly, PTEs inhibit plant nutrient availability and uptake. PTEs may also affect soil organisms, leading to adverse impacts on soil organic matter decomposition, nutrient supply and nutrient recycling. Therefore, determination and understanding the PTEs distribution and bioaccumulation in agro-ecosystem is vital to develop protection measures for health risks to soil organisms, animals, and humans.

## **2.7. Potentially toxic elements in East African agro-ecosystems**

East African agro-ecosystem (EAA) is characterized by complicated socio-ecological system which is driven by delicate environmental and climatic fluctuations (Wynants *et al.*, 2019). The EAA incorporates crop cultivation (in arable land), animals husbandry, preservation exercises, fishing (aquaculture) and rustic residential areas. This makes EAA a complex assembly, the framework that is exceptionally troublesome to screen and oversee. The EAA is domestic to distinctive common and anthropogenetic exercises that emphatically and contrarily impact its usefulness. Agricultural and other human activities in or in the vicinity ecosystem have significant ecological and biological impacts (Moss, 2008). The use of agrochemicals in farming areas in most

least developed countries is increasing, but have been observed to be there is insignificant guidance on the how to use them eco-friendly (Steffen *et al.*, 2018); this is usually exacerbated by the unavailability of documentation and guideline of agrochemicals concentration limits to be used to guarantee high productivity and environmental quality (Matowo *et al.*, 2020). The available fertilizer recommendations in most EA countries are old with more than 30 years, thus, outdated to be used in the existing environmental and climatic conditions due to tremendous climatic and environmental changes that have happened in the last thirty years. Of specific fear, the utilization of mineral fertilizer and other agrochemicals is regularly used without legitimate instruction from rural extension experts (Isham, 2005). The rate of agrochemicals utilized in crop farming in EA has significantly increased (Nonga *et al.*, 2011). Hence, the application of agrochemicals is higher than required by plants or beyond limits resulting in environmental contaminations (Khani *et al.*, 2017). In parallel, the challenge of PTEs contamination has been recognized over Africa (Nriagu, 1992), where PTEs accumulation in AE is driven by agriculture intensification, urbanization, climate and land-use change, industrialization, and farming systems. Alongside administrative arrangements, these collectively impact the agro-ecosystem, driving straightforwardly and by implication to either economically expanded food production or a decline in food production and agro-ecosystem sustainability (Fig. 3). Hence, suitable thought of PTEs build-up in agro-ecosystems is fundamental in setting up good agronomic systems and administration frameworks to guarantee economical agro-ecosystems efficiency and diminished contamination dangers. This segment traces the contamination hazard of PTEs and its consequences on the sustainability of AE.

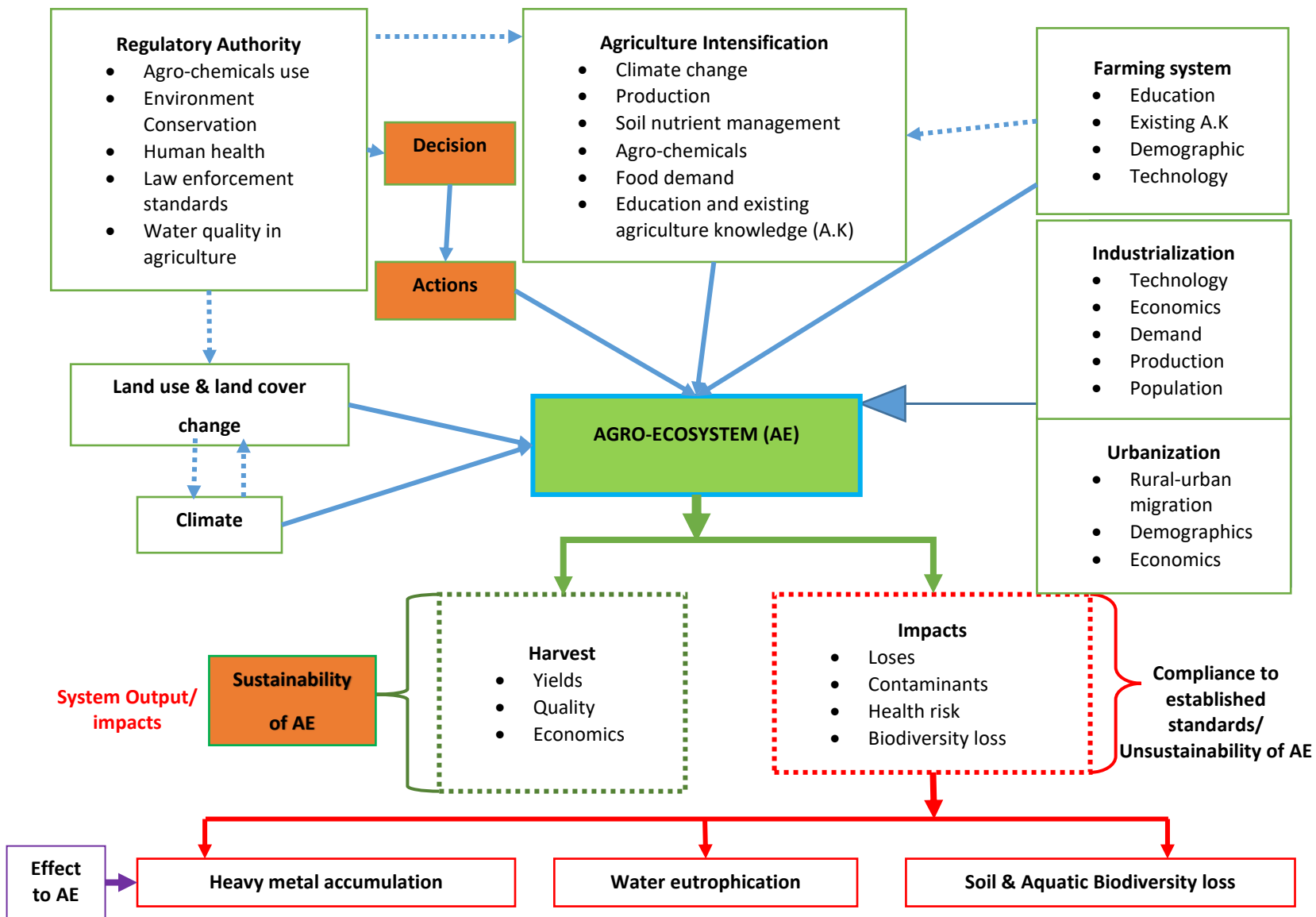
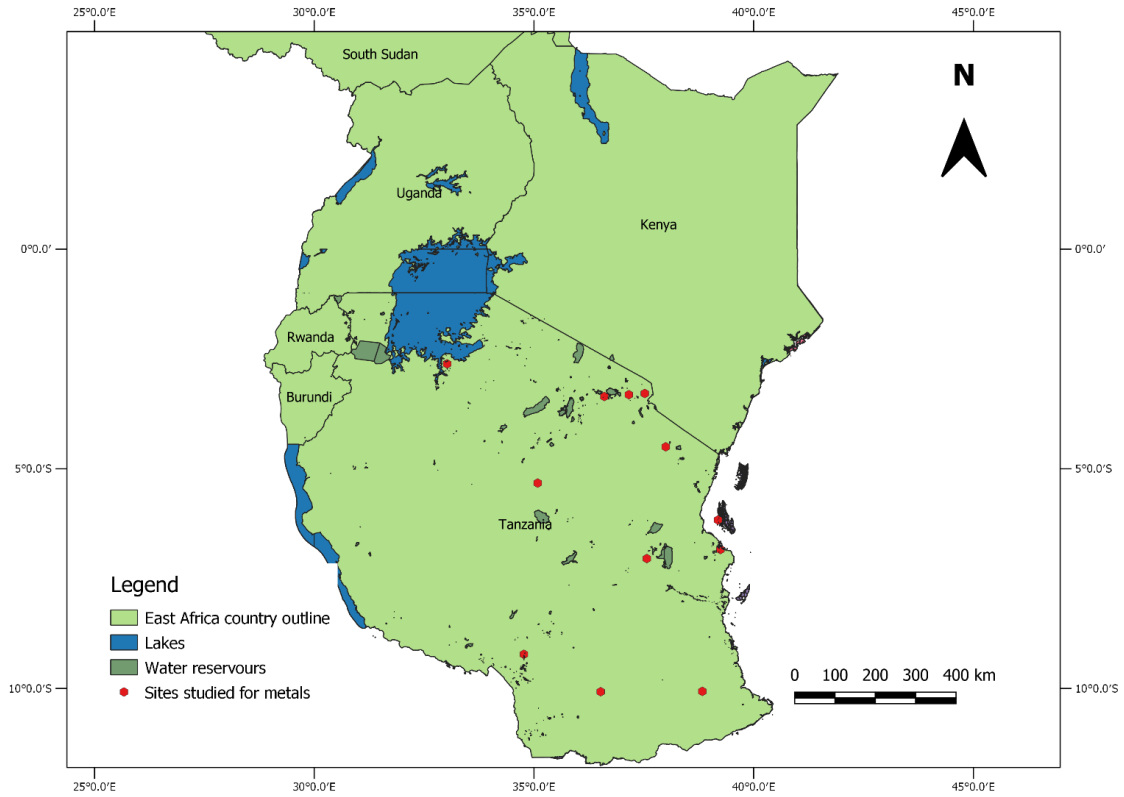


Figure 3: Diagrammatic representation of drivers and factors that govern PTEs accumulation and distribution in AE

The Fig. 3 shows the diagrammatic representation of drivers and factors that govern PTEs accumulation and distribution in AE. Where bolded words in square boxes are factors, drivers are presented by bullets, expected system impacts/output is shown in dotted boxes; dotted line shows the indirect or limited influence of a factor on AE or other factors/driver, and complete or direct influence or impact of the factor or driver to AE is shown by a solid line.

The East African agro-ecosystem covers a widespread cluster of natural sceneries and seriously human activities, quickening fast changes to EAA. The temporal scope started in the early 1970s, a period known by low sub-urbanization near farming areas, high rainfall, low runoff, and low anthropogenic impacts. This was taken after by the presentation of pastoralism, intensive agriculture, and urbanization within 1980s, which heightens nearby to worldwide associations leading to higher production, increased area under cultivation, forest clearing, and PTEs contaminations, an expanded zone beneath development, deforestation, water pollution, and poisonous metal contaminations. The “EA (Fig. 4) hosts a higher diverse environmental resource, such as substantial river basins (i.e., Mara, Usangu, Rufiji, Kilombero) and numerous major rivers (i.e., Great Ruaha River, Nile, Malagarasi, and Mara River). The contemporary region is a centre for aquaculture, dairy farming, field crops, vegetable and perennial crop production, fishing, and culturally diverse urbanized and rural populations” (Kashaigili *et al.*, 2006). At present, limited operative managing options are in place to control and regulate the use of agrochemicals, eutrophication, soil nutrient exhaustion, and PTEs contamination.



**Figure 4: The distribution of sites studied for PTEs accumulation and distribution in topsoils in East African countries (source: author)**

## 2.8. East Africa agro-ecosystems (EAA) and farming systems

The EAA in this section is used as a case study to address the PTEs pollution in farming areas. The “EAA is complicated, with multiple connections that make agro-ecosystem management difficult. Crop production in EAA is primarily rainfed, with food crops (sweet potatoes, maize, millet, beans, etc.) and cash crops (coffee, tea, cashew, and banana) being cultivated in the highlands, and irrigated crops (rice, horticultural crops, and sugarcane) being farmed in the lowlands. The majority of animal production is free-range, with a few exceptions where zero-grazing is used. Animal rearing and crop production are carried out simultaneously in various zones, e.g. Lake, Southern Highland and Eastern Zone of Tanzania and Kenya, especially following crop harvest (Kimaro, 2019). Irrigation farming has increased the number of times crops grown within the same field per year or season from one to more than five times; this additionally complicates monitoring and management of AE (Nonga *et al.*, 2011). With the higher price of its produce and its short cropping cycle, horticultural crop production is particularly active in EAA and seriously managed with agrochemicals (Kibassa *et al.*, 2013). Agro-ecosystem complexity is

also increased by the presence of populations with diverse ethnic and socioeconomic values that affect land use, planning, and tenure. All of these factors make agro-ecosystem complex and fragile, making it difficult to manage. The introduction of new technology increased the usage of agro-ecosystem since a wide area can be easily changed to farmland. However, less usable land has been used for animal farms and aquaculture, reducing the amount of ecosystem land that can be maintained as conserved areas. Agrochemical use has increased as a result of agriculture intensification, which has led to wider adoption of monoculture agricultural systems for better mechanization. While increased use of agrochemicals improves productivity per unit area, it also strains the agro-ecosystem due to increased pollution concerns (Jepson *et al.*, 2014). Different elements and drivers impact and pressure any agro-ecosystem, for instance, regulatory authorities, which govern agrochemicals and their quantity to be employed (Fig. 3), thus determining agro-ecosystem production and sustainability” (Mng’ong’o *et al.*, 2021).

Several farming systems exist in East African agro-ecosystem, including: “(a) Irrigated farming system (IFS): This system comprises both large and smallholder farmers and is popular in watered flat land areas such as Sudan's Gezira and Tanzania's Usangu, Kilombero, and Rufiji basins. In East Africa, the IFS covers about 35 million hectares of arable land (FAO, 2000). IFS crops include vegetables, flowers, paddy rice, and sugar cane, and it is frequently augmented by rainfed agriculture. (b) Tree crop farming system: This farming system is dominated by cash crops (tea, coffee and oil palm) and food crops (mango, avocado, etc.), while annual crops are cultivated within tree lines for subsistence and from time to time few cattle are raised; (c) Highland perennial farming system; this is typical in highland areas for perennial crops such as banana and coffee, with sweet potato, beans, and cereals supplemented. This technique is widely used in Uganda, Rwanda, Burundi, and Tanzania's subhumid and humid agro-ecological zones. Smaller farm sizes and yield returns characterize the system (FAO, 2015). (d) Mixed farming system: This farming system is mostly found in subhumid or humid agro-ecological zones at mid to high (1800-3000 m) altitudes. Animal production (e.g., sheep, goats, and cattle) and crop cultivation (potatoes, maize, beans, millet, and peas) are both parts of the system. The system has mainly one single cropping season; if there are two, the second is usually relatively short. In general, challenges such as deteriorating soil nutrients owing to soil erosion, uncontrolled pesticide use and contaminations seriously plague East Africa's farming system” (Mng’ong’o *et al.*, 2021).

## 2.9. Accumulation PTEs on soils and water in agro-ecosystem

### 2.9.1. Sources of PTEs in agro-ecosystem

Natural and anthropogenic sources of PTEs in agro-ecosystems are well-known; natural sources comprise dust emissions, volcanoes, and weathering products of metal-rich rocks, whose intensity varies across the landscape, relying on other activities and temperature changes (Shefali *et al.*, 2019). Agrochemicals such as pesticides, growth regulators, fertilizers, and herbicide use, mineral mines, and contaminated surface runoff are all examples of key anthropogenic sources (Fig. 5).

Soil parent materials are geological sources of PTEs; for instance, phosphate mineral rocks are often have high in Pb, Cd, and Cr (Lema *et al.*, 2014). Different circumstances like changes in redox reactions, pH and temperature variability can activate these elements to accessible forms in soil and water. Soil erosion transports soil particles from one location to another, resulting in PTEs being distributed more widely in agricultural land and aquatic bodies (Nagajyoti *et al.*, 2010). In many parts of the world, i.e., Spain, China, Iran, Kenya, and other African countries, the PTEs concentration in agricultural soils has been observed to increase in the last 30 years (Sayo *et al.*, 2020). Furthermore, in East Africa, the lack of uniform agricultural management and implementation of cooperative environmental conservation regulations has accelerated agro-ecosystem degradation (Mungai *et al.*, 2016). Industrial, agricultural, mining, and residential wastes have been recognized as the principal cause of PTEs deposition in agricultural soils and water in East African AE (Simon *et al.*, 2016). Based on Machiwa (2010) study conducted in Geita district, the level of Hg was higher (3.2-69.3 g/kg) in farming regions closest to gold mines and surpassed the permitted limit of 0.005 mg/kg. Furthermore, Almås and Manoko (2012) found a high arsenic concentration (720 mg/L) in water samples in locations near mining operations in Geita and Mara regions-Tanzania.

The PTEs pollution hazards are exacerbated by agricultural intensification and increased fertilizer use (Mshana, 2015). In Tanzania and Nigeria, the study by Awotoye (2011) discovered that soils amended with mineral phosphates rocks had higher Zn, Cu, Pb, and Cd than soils not modified with phosphatic fertilizer, but their values were in the tolerable range with exception of Cd (5.30 µg/g dry wt) which exceeded FAO tolerable limit (3 µg/g dry wt) in agricultural soils. For that reason, excess P fertilizer use could lead to increased PTEs in soils and water. Furthermore,

fertilizer application was observed to increase PTEs in agricultural soils in Northern Iran as reported by Malidareh *et al.* (2014), who reported higher levels of As, Pb and Cd on paddy fields after phosphatic fertilizer application, the PTEs levels before fertilization were as follows: “As (0.001-0.007 mg/kg) and Pb (0.066-0.103 mg/kg), whilst after P-fertilization, PTEs increased to As (0.10-0.30 mg/kg) and Pb (0.201-0.447 mg/kg), which surpassed the FAO maximum permitted limits (As = 0.2 mg/kg and Pb = 0.1 mg/kg)” (Koleleni & Mbike, 2018). This scientific research suggests that the use of mineral fertilizers, insecticides, and other agrochemicals in farming areas may be an important source of PTEs in EAA; management and mitigation strategies have to be in place to ensure higher land productivity, environmental quality and sustainability. But also, there should a specific and clearer distinction management options for PTEs due to agricultural activities (which will be amended by agricultural management plans) and those due to mining, industry or urbanisation, which are totally different sectors over which the farmers have little control.

### **2.9.2. Exposure pathways of PTEs in soils and water**

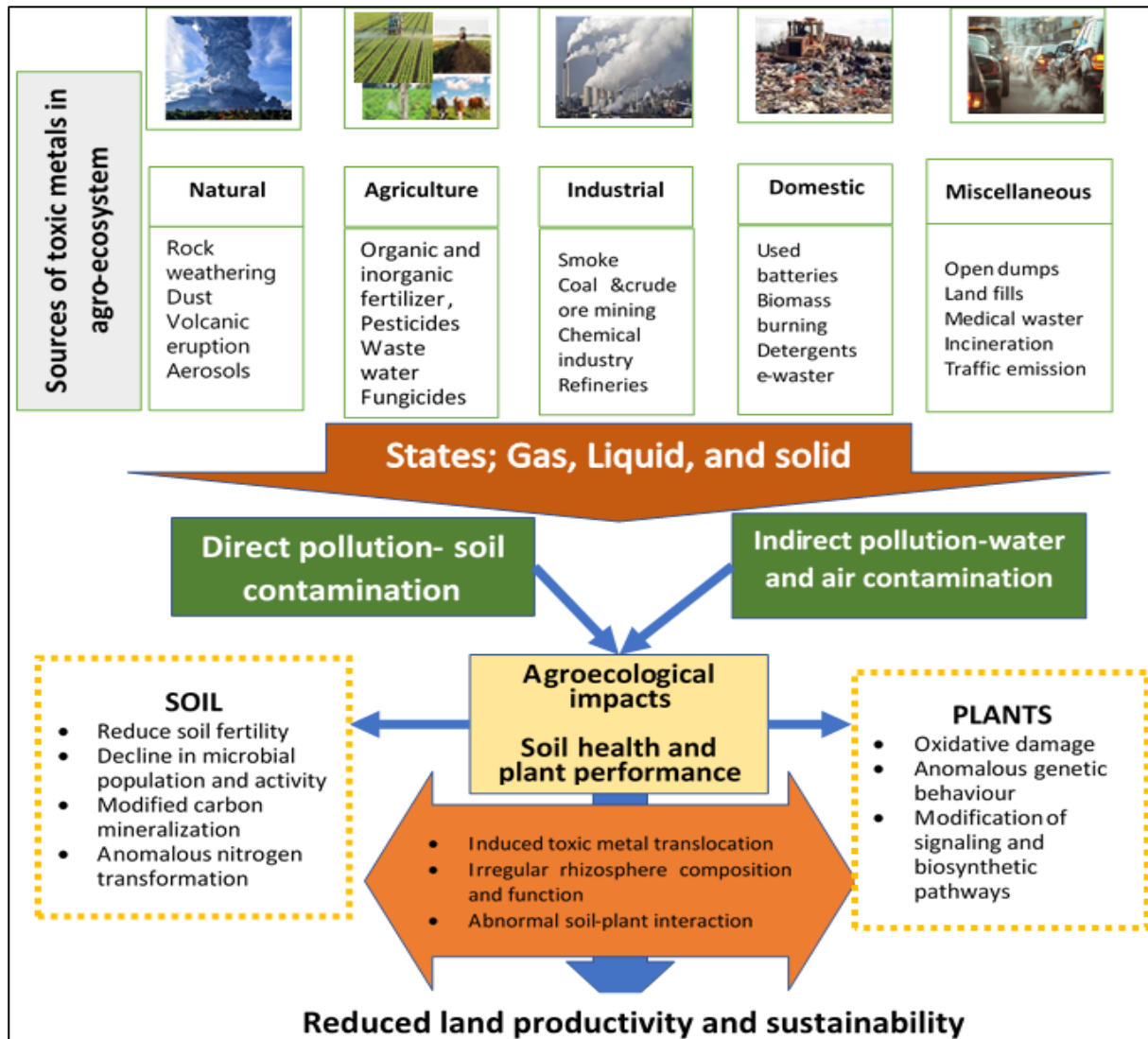
The “PTEs in soil accumulate through several paths from various sources. Point source pathways transmit PTEs from urban garbage, factories, and other sources directly to soil and water bodies (direct pollution); from either single or multiple sources it can be either accidentally or intentionally by human activity (Tutic *et al.*, 2015). This pathway is most observed in developing countries due to the lack of stringent restrictions and procedures on the release of wastes into the environment (Nriagu, 1992). The point source pathway is common in urban areas with significant wastewater, dust, and aerosol generation due to a large number of companies and overpopulation, especially in developing nations that have inadequate waste management systems (Kinuthia *et al.*, 2020). The recent studies conducted by Mungai *et al.* (2016) and Kihampa (2015) in Nairobi-Kenya and Dar es salaam-Tanzania found that mining tailings, urban effluents, and industrial waste were important sources of PTEs in urban agriculture; this indicates that however, point source pollution has been decreased but still exist in EAA” (Mng’ong’o *et al.*, 2021).

Secondly, PTEs also can occur in soils and water in the area via non-point source pathways (NPSP), in which PTEs are gradually build up in soils and water from unknown sources; this may be via materials and equipment such as fertilizer, insecticides, herbicides, and other agrochemicals; irrigation with treated and untreated wastewater; and surface water runoff from urban or industrial

regions but also secondary release from areas that received the pollution. For example, floodplains re-releasing may also potentially increase PTEs in agricultural soils. The use of wastewater in irrigation farming minimizes the demand for freshwater withdrawals and serves as a potential nutrient supply (K, P, N) for plants; it also poses a risk of soil pollutants addition (Sayo *et al.*, 2020). Sayo *et al.* (2020) found higher PTEs concentrations i.e., 0.48 to 1.83 mg/L (Cu), 1.43 to 4.61 mg/L (Zn), 0.02 to 0.35 mg/L (Cd), and 0.01 to 2.12 mg/L (Pb)) in wastewater used in vegetable farming in Embu county-Kenya, which exceeded WHO permitted limit for Cu, Cd, Zn, and Pb concentrations in wastewater utilized in agriculture/irrigation, i.e., 0.2 mg/L, 0.01 mg/L, 2 mg/L, and 0.5 mg/L, respectively (WHO, 2006). The NPSP is not easily detectable until there is a larger level of PTEs and a possible observable consequence. PTEs from herbicides, fertilizers, pesticides (i.e., Co, As, Ni, Cr, and Pb from glyphosate-based herbicides and insecticides (Defarge *et al.*, 2018)), contaminated urban runoffs, growth hormones, home detergents, irrigation water, and agricultural machine leaks are all part of this pathway (Table 1). As a result, a better knowledge of PTEs exposure pathways in agricultural areas is critical for developing rapid control tactics and preventing further PTEs increases in the agro-ecosystem.

**Table 1: The PTEs sources in agricultural soils and associated PTEs**

Sources	Formulations	Potential PTEs	Reference
Glyphosate based herbicides	Glyphosan, clinic Ev, Bayer GC, and glyfos	As, Pb, Cr, Ni, and Co	Defarge <i>et al.</i> (2018)
Leakage from farm machines	Smoke, liquids	Pb, Cr, Cu	Shemdoe (2010)
Urban runoffs	Stormwater	Zn, Cr, Va, and Pb	Mahugija and Sheikh (2018)
Pesticides formulation	Eyetak, matin, Folpan, and polysect	As, Ni, Cr, and Co	Defarge <i>et al.</i> (2018)
Industrial wastewater		Zn, Cu, Cr, Pb, and Cd,	Sayo <i>et al.</i> (2020)



**Figure 5: Potential significant sources of PTEs and their effects in agro-ecosystem**

### **2.9.3. Drivers for increased PTEs in East Africa agro-ecosystem**

Higher PTEs levels in agro-ecosystem can be caused by both pedogenic (related to weathering of parental materials) and anthropogenic activity (Naidu & Bolan, 2008). The PTEs generated from geologic soil materials are generally less and not easily available for plant uptake and pose a lower environmental concern (Khan & Ansari, 2005). Several factors/drivers in East Africa are expected to hasten the buildup of PTEs in agro-ecosystems. Important drivers which influence PTEs distribution in AE include agricultural intensification, population growth, peri-urban urbanization and industrialization, natural processes (weathering), and mining tailings.

*Population growth;* In East Africa, where the population is growing at a pace of 6.2%, there are more mouths to feed, necessitating more food production to satisfy raised demand (Dániel *et al.*, 2019). As the population grew, so did urbanization, which reduced available agricultural land as it was used for settlements and industries. As a result, higher agrochemicals use (insecticides, fertilizer, growth regulators, and herbicides) is used to assure maximum productivity per unit area (Jepson *et al.*, 2014). Furthermore, population growth has resulted in increased production of home and industrial wastes, which, once improperly managed, could be discharged into soils and water, raising PTEs levels (Fig. 5). Based on studies conducted in two major cities of East Africa (Nairobi-Kenya and Dar es Salaam-Tanzania), it was observed that higher PTEs levels were in agricultural fields which were located along major highways, which might be associated with engine leakage, vehicular emission and other highway waste production (Mwegoha & Kihampa, 2010). However, population growth might be seen as a driving force behind other variables that hasten PTEs contamination. Because little attention is paid to the problem, currently, there is limited evidence on the impact of population increase and hazardous metals deposition in soils and water in metropolitan areas of East Africa.

*Agricultural intensification:* The reduction in arable land availability as a result of increasing urbanization dictates agricultural intensification through the use of improved crop cultivars and high use of agrochemicals to raise productivity (Fig. 5 and Table 2) (Clover, 2003). The currently utilized agrochemicals are reported to contain chemicals linked to various PTEs contaminants, which, when used in excess, might raise PTEs levels in agro-ecosystems, as mentioned in previous sections (Mungai *et al.*, 2016). Most farmers do not utilize agrochemicals correctly, which

accelerates the accumulation of PTEs in soils and water in the agro-ecosystem. Thus, examining and creating awareness of PTEs accumulation and agricultural intensification is key when planning management strategies required for soils and water management to balance environmental quality and high land productivity (high yields).

**Table 2: The Summary of PTEs Amount ( $\mu\text{g/g}$  dry wt) which can Potentially Accumulate in Agricultural Soils from Different Materials (Sewage sludge, Mineral Fertilizer, Compost, Pesticides, and Farmyard Manure) used in Agricultural Fields**

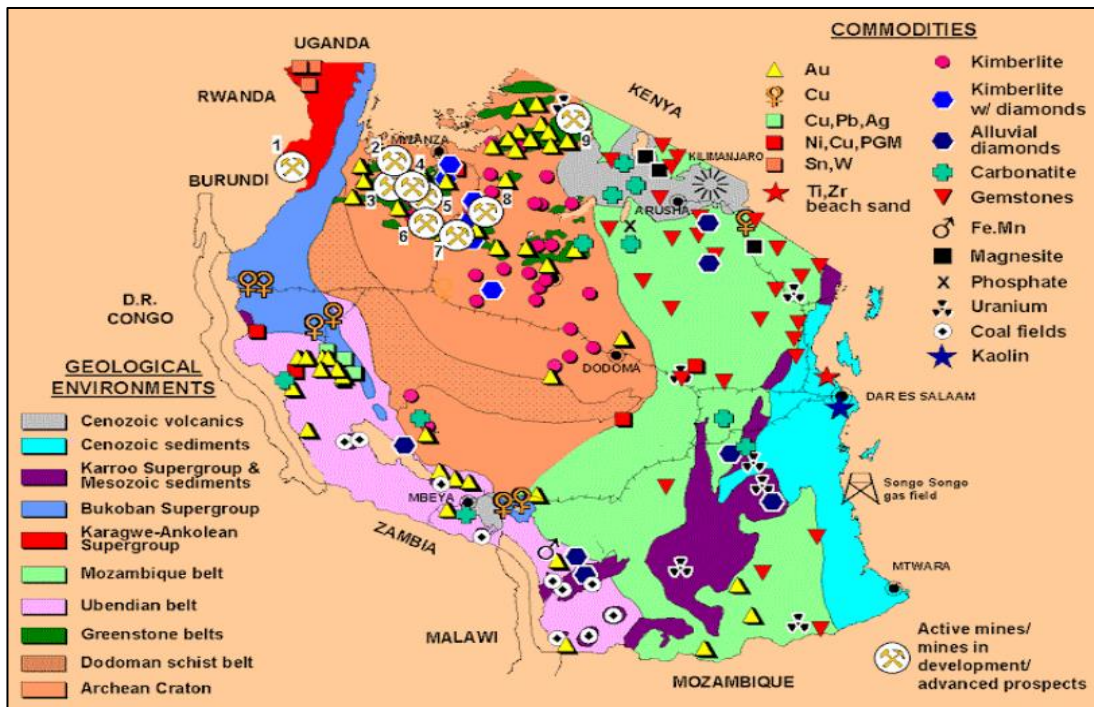
PTEs	Lime	Sewage sludge	Nitrogenous fertilizer	Phosphatic Fertilizer	Pesticides	Compost	Farmyard manure
Ni	10-20	6–5300	7–34	7-38	-	0.9-279	2.1–30
Cd	0.04-0.1	<1–3410	0.05-8.5	0.1-190	-	0.01–100	0.1-0.8
Cu	2-125	50–8000	-	1-300	-	13–3580	2-172
Cr	10-15	8.40–600	3.2–19	66–245	-	1.8–410	1.1–55
Zn	10-450	91–49000	1-42	50-1450	-	82–5894	15-556
Pb	20-1250	2–7000	2–120	4-1000	11-26	1.3-2240	0.4-27

*Increased urbanization and industries in peri-urban areas:* Increased industry production has hastened the production of polluted wastes (aerosols, wastewater, and dust), which could end up in the agro-ecosystem. Generally, PTEs pollute more farming areas closer to cities with higher number of industries than cities with fewer industries as less contaminated waste is produced (Mwegoha & Kihampa, 2010). For example, runoffs used for irrigation in several paddy farming areas, particularly in the Lake Zone and Southern Highlands of Tanzania, have been documented to have increased levels of plant nutrients (N and P) and PTEs. The PTEs are also released into the environment by industrial operations such as mining (Fig. 5). For example, the use of mercury in gold mines resulted in higher levels of mercury in soil and sediment in agro-ecosystems near the Geita gold mines in Tanzania (Mataba *et al.*, 2016).

*Natural sources;* Rock weathering could produce significant amount of PTEs to the environment, which is carried over a long distance with wind and water (Fig. 5). This is dependent on the chemical composition of the rock, as well as weather and environmental conditions (Abdu *et al.*, 2011). Metal concentrations in geologic materials have been discovered to be high; for example, geologic materials are rich in Cr, Hg, Cd, Pb, Co, Cu, Zn, Ni, and Sn. Volcanic materials, on the other hand, are rich in Al, Pb, Hg, Zn, Ni, and Cu (Nagajyoti *et al.*, 2010). Forest fires, on the other hand, contribute to environmental PTEs to some extent by producing volatile PTEs such as Se and

Hg (Srivastava *et al.*, 2017). Banzi *et al.* (2015) found significant quantities (mg/kg) of Zn (13.8), Pb (25.2), Cd (13.8) and Cu (10.1) in bare or non-cultivated land in Southern Highland Tanzania during their investigation (Table 3-8). This suggests that increased amounts of PTEs can occur as a result of natural sources and processes. However, anthropogenic processes can impact the availability of PTEs that are naturally present due to changes in redox.

*Mining tailing:* The PTEs such as Hg, Pb, Cd, Cu, and Cr can be determined in drainages from mining regions, which are either untreated or inadequately treated before being released into rivers or the environment (Fig. 6). Because most PTEs have related health risks to humans and animals, drainage and runoffs from mining regions must be avoided from entering farming land and water bodies untreated/partially treated to stop PTEs contamination and associated risks. The study by Mataba *et al.* (2016) on the PTEs distribution in the marine ecosystem near Nyamongo gold mine in Geita reported increased Hg and As concentration in water which was observed to be associated with drainages from mining areas; nevertheless, the study determined PTEs were within WHO maximum permissible limits for drinking water (As = 0.01 µg/L, and Pb = 0.006 mg/L) (WHO, 2018).



**Figure 6: Areas with different mineral mines that are potential PTEs sources in agro-ecosystem (Ministry of Minerals-Tanzania, 2006)**

## 2.10. Distribution of PTE in East African agro-ecosystems

There is currently no joint effort in East Africa to characterize the accumulation of PTEs in topsoils in agro-ecosystems (AE); additionally, there is scant evidence on PTEs studies in AE, with currently available studies focusing on PTEs in mining areas, disregarding other ecosystems such as AE that may be negatively impacted by increased PTEs concentrations. While the socio-cultural and environmental contexts of AE in East African countries, such as South Sudan, Burundi, Uganda, Tanzania, Democratic Republic of Congo, Kenya, and Rwanda, are relatively different, they are all under pressure from the same variables and drivers.

In the remainder of this review section, Tanzania is used as an example to illustrate the distribution of PTEs in topsoils in EAA in order to provide a larger picture of AE quality and sustainability. Land use and farming techniques have a significant impact on PTEs distribution; farming practices that decrease organic carbon, raise soil pH, or speed up weathering process have an impact on the accumulation and availability of PTEs (Zhao *et al.*, 2010). In studies conducted in Mtwara maize farming areas, farms positioned near gold mining areas were shown to have higher levels of PTEs in soils (Table 3-8) than farms located further away from mining areas (Koleleni & Mbike, 2018).

As a result, an adequate assessment of PTEs levels in agro-ecosystem is essential to guarantee that they are within acceptable limits for environmental safety and human health. Various studies on PTEs distribution in different land use in Tanzania found that most areas had PTEs concentration levels below FAO and WHO permissible limits (WHO, 2006, 2018). However, several sites (about 25%) had PTEs concentrations that exceeded FAO and WHO regulatory limits (Tables 3-9).

Due to the fact that coffee and vegetable cultivation has traditionally been treated with several Cu-based fungicides, coffee and vegetable growing areas have been observed to have a higher buildup of Cu, Pb, and Cr (Senkondo *et al.*, 2015, 2014). Surface water runoffs from mining sites observed to have increased PTEs in soils and rice grains in paddy farming areas in Mwanza region, such as Cr (19.14-39.40), Cu (70.1-169), Pb (19.39-28.50), Zn (59.8-158), and Cd (0.48-0.88 mg/kg). “The determined values were observed to exceed WHO and USEPA maximum permissible limits for PTEs in agricultural soils (i.e., 2, 0.1, 1, 0.1, and 5 mg/kg, for Cu, Pb, Cr, Cd, and Zn, respectively) and concentration of PTEs in rice grains were Cu (0.8-3.7 mg/kg), Cd (0.001-0.12 mg/kg), Pb (0.001-0.29 mg/kg), Cr (0-0.03 mg/kg), Zn (4.10-48.7 mg/kg), and Hg (0.1-11.4 mg/kg)” (Simon *et al.*, 2016). The proportion of PTEs found in soils, plant, and grains samples warn that crops grown in PTEs-rich locations or those getting contaminated runoff from mining or metropolitan areas may have an impact on soil and water quality, as well as food quality, thus, posing health risks.

Furthermore, Mahugija and Sheikh (2018) found that urban farms located closer to automobile activities and industries in Dar es Salaam and Zanzibar had higher concentrations (mg/kg) of Pb (0.02-271), Cu (0.1-167), and Zn (0.27-419.2), showing that industrial activities and combustion of fossil fuels might be responsible for increased PTEs accumulation and distribution in agro-ecosystem (AE). Additionally, “soil PTEs concentrations were higher in locations with vehicle workshops than in those without, signalling anthropogenic influences. This suggests that unmanaged or unmonitored runoff from urban and industrial regions could be a significant source of PTEs contamination and spread in peri-urban farming areas' water and soils. The study discovered that Zn, Cu, and Pb concentrations were above Tanzania and WHO acceptable levels of 150 mg/kg and 100 mg/kg, respectively, in 51%, 40% and 18% of studied regions. Therefore, the distribution of PTEs in topsoils changes depending on the land use activities and anthropogenic activities in a given area. Thus, may pose a health danger and jeopardize soil and water quality, as

well as viability of AE for long-term food production. This necessitates a thorough assessment of PTEs in soil and water in urban and peri-urban farming areas” (Mng’ong’o *et al.*, 2021).

**Copper (Cu):** Copper distribution in topsoils among land use varied significantly ( $P < 0.05$ ) (Table 3). Farming areas had higher Cu values (mg/kg), especially in farming areas that have or historically used higher Cu-based agrochemicals biocide such as in vegetable production (7.19), coffee farming (312), paddy farms (14.6), and maize farms (82.8 mg/kg). It was observed that among 445 soil samples studied, 26 samples had Cu above maximum permissible limits (100 mg/kg). This suggests that determined Cu could contaminate environment and cause phytotoxicity effects on crops. However, a study conducted in Italian soils by Fagnano *et al.* (2020) found that Cu concentrations of 100 mg/kg were insufficient to cause harmful effects to plants, soil invertebrates, and animals, and their hazard might be excluded. Approximately 45.2% of soil samples studied from conventional coffee farms had Cu concentration above 100 mg/kg, a maximum permissible limit of Cu in agricultural soils in Tanzania (URT, 2007). Industrial and mining areas contribute more to copper distribution in peri-urban soils; Herman and Kihampa (2015) found a higher Cu concentration in soils sampled in mining and industrial areas in Singida and Zanzibar. Out of 108 soil samples (Table 3) taken from industrial areas, it was found 6.5% of studied samples had Cu concentration exceeding maximum permissible limit.

**Lead (Pb):** In Tanzania, Pb concentration in various land uses were found to be particularly high in agro-ecosystems near mining and industrial areas (Table 4). Based on the study carried out by Machiwa (2010), Koleleni and Mbike (2018), and Banzi *et al.* (2015) found that paddy and maize growing areas had higher Pb concentrations (19.7 and 19.1 mg/kg, respectively). Moreover, studies observed that some industrial sites, near mining areas, urban agriculture soils, and bare land had higher Pb concentrations, such as 51.07, 13.29, 15.51, 24.7 mg/kg, respectively, but they were all within Tanzania's Pb permissible limits (100 mg/kg); however, the majority of them were beyond USEPA Pb maximum permissible limit (USEPA, 1992). This implies that any crop planted in these places is likely to collect Pb, posing a health risk to those who consume it. The higher PTEs in natural or bare land in some parts of Ruvuma (Table 4) suggest that geological materials contain Pb in a significant quantity (Banzi *et al.*, 2015), which can be transmitted to surrounding agro-ecosystems by runoff and erosion.

**Table 3: The Summary of Cu-Distribution in Topsoils among Different Land Use or Soil Cover Types in Tanzania**

Land use/cover type		Region	Total number of samples		Soil concentration (mg/ Cu kg dry wt)				Regulatory values >100 mg Cu/kg		Extraction Method	References
Code	Description		Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	4.1	14.6	15.0	22.8	5.9	0	0	DTPA	Machiwa (2010)
IA	Industrial areas	Zanzibar	108	24.3	51.0	51.1	167.0	43.6	7	6.5	Aqua regia	Mahugija and Sheikh (2018)
CM	Cereals (Maize)	Lindi	20	4.5	82.8	70.1	169.2	1.3	5	25.0	EDXRF	Koleleni and Mbike (2018)
Mix W	Mixed woodland	Tanga	54	12.2	3.0	2.7	8.2	2.1	0	0	DTPA	Meliyo <i>et al.</i> (2015)
PIC Tea	Permanent industrial crops (tea)	Njombe	24	5.4	0.2	0.2	0.3	0.17	0	0	DTPA	Kitundu and Mrema (2006)
Veg	Vegetables	Morogoro	9	2.0	0.4	1.5	7.2	0.3	0	0	DTPA	Lugwisha (2016)
Ctf	Soils in treated coffee farms (tf)	Arusha & Kilimanjaro	31	7.0	312.0	281.5	806.0	177.8	14	45.2	Aqua regia	Senkondo <i>et al.</i> (2014)
Cutf	Soils in untreated coffee farms (utf)	Arusha & Kilimanjaro	5	1.1	29.0	27.0	32.0	6.0	0	0	Aqua regia	Senkondo <i>et al.</i> (2014)
BL	Bare land	Ruvuma	84	18.9	10.0	9.90	25.1	4.1	0	0	EDXRF	Banzi <i>et al.</i> (2015)
GL	Grassland	Kilimanjaro	42	9.4	8.5	8.8	24.7	6.0	0	0	FTMIRS	Mathew <i>et al.</i> (2016)
UAS	Urban agriculture soils	Dar es salaam	24	5.4	13.9	15.5	21.1	4.1	0	0	Aqua regia	Mwegoha and Kihampa (2010)
NMA	Near Mining areas	Singida	26	5.8	14.5	15.0	29.4	5.2	0	0	Aqua regia	Herman and Kihampa (2015)
Total			445	100	<b>44.9</b>	15.0	806.0	21.4	<b>26</b>	<b>5.8</b>		

“NB: FTMIRS means Fourier Transform Mid-Infrared reflectance Spectroscopy, EDXRF means Energy Dispersive X-ray Fluorescence, DTPA means Diethylenetriamine pentaacetate. The table is adapted with modification from Ballabio *et al.* (2018)”

**Table 4: Summarized Pb distribution in topsoils from different cover types or land use in Tanzania**

Land use/cover type		Region	Total number of samples		Concentration of Pb (mg/kg dry wt)				Regulatory Value Conc>200mg/kg		Extraction Method	References
Code	Description		Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	6.2	19.4	19.7	28.5	6.0	0	0	DTPA	Machiwa (2010)
CM	Cereals (Maize)	Lindi	20	6.9	14.3	19.1	20.3	0.4	0	0	EDXRF	Koleleni and Mbike (2018)
Veg	Vegetables	Morogoro	9	3.1	0.7	0.8	1.2	0.3	0	0	DTPA	Lugwisha (2016)
BL	Bare land	Ruvuma	84	29.1	25.2	24.7	42.5	7.8	0	0	EDXRF	Banzi <i>et al.</i> (2015)
IA	Industrial Areas	Zanzibar	108	37.4	32.5	51.1	111.5	35.8	0	0	Aqua regia	Mahugija and Sheikh (2018)
UAS	Urban agriculture soils	Dar es salaam	24	8.3	16.9	15.5	22.9	1.8	0	0	Aqua regia	Mwegoha and Kihampa (2010)
NMA	Near Mining areas	Singida	26	9.0	13.6	13.3	22.2	3.5	0	0	Aqua regia	Herman and Kihampa (2015)
<b>Total</b>			<b>289</b>	<b>100</b>	<b>17.5</b>	<b>19.1</b>	<b>111.5</b>	<b>7.9</b>	<b>0</b>	<b>0</b>		

**Table 5: Summarized Cr III distribution in topsoils from different cover types or land use in Tanzania**

Land use/cover type		Region	Total number of samples		Concentration of Cr III (mg Cr III/kg dry wt)				Regulatory Value Conc>100mg CrIII/kg		Extraction Method	References
Code	Description		Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	10.0	19.1	18.4	39.4	8.1	0	0	DTPA	Machiwa (2010)
BL	Bare land	Ruvuma	84	46.7	31.1	30.4	54.9	7.4	0	0	EDXRF	Banzi <i>et al.</i> (2015)
UAS	Urban agriculture soils	Dar es salaam	24	13.3	349.0	376.0	502.3	113.5	24	100	Aqua regia	(Mwegoha and Kihampa (2010)
NMA	Near Mining areas	Singida	54	30.0	28.2	28.5	33.4	4.1	0	0	Aqua regia	Bitaka <i>et al.</i> (2009)
<b>Total</b>			<b>180</b>	<b>100</b>	<b>106.8</b>	<b>29.5</b>	<b>502.3</b>	<b>33.3</b>	<b>24</b>	<b>13.3</b>		

**Chromium (Cr):** The Cr concentration in topsoils from various land use was found to vary between locations and land use (Table 5). Where “Cr concentrations (mg/kg) were greater in bare land (31.10), urban agriculture (348.93), and near mining areas (28.50) based on 180 samples collected, higher Cr concentration in bare land is suggesting that higher levels may be attributable to geological compositions (Table 5). The higher concentration of Cr in urban agriculture were observed and were beyond the acceptable limit of 100 mg/kg, indicating that plants growing in those sites may be exposed to Cr toxicity, potentially posing a health risk to humans (Mwegoha & Kihampa, 2010). However, new discoveries show that Cr toxicity to plants and food items is relatively low, owing to the fact that Cr is less accessible to plants and microorganisms in soils due to high interactions to other metals (Visconti *et al.*, 2019). Among 180 soil samples studied, 24% had Cr above Tanzania's maximum permissible limit (100 mg/kg) (URT, 2007). The study by Simon *et al.* (2016) and Machiwa (2010) found a significant concentration of Cr (19.14 mg/kg) in paddy farming areas in Lake Zone Tanzania (Table 5) which was within Tanzania maximum acceptable limits (100 mg/kg) but was higher than the USEPA's maximum Cr permissible concentration limit in agricultural soils of 1 mg/kg (URT, 2007; USEPA, 1992). This means that depending on which maximum limit values are utilized to make conclusion or contamination decision, soils might be classified as polluted or unpolluted. Therefore, there is a need for unified regulatory values to be established for harmonized environmental quality assessment. However, it may be tough due to divergences in biogeochemistry of a specific area and land uses, but is possible” (Mng’ong’o *et al.*, 2021).

**Cadmium (Cd):** The Cd concentrations in topsoils from various land use were found to be particularly high in locations close to or near mining areas (7.4 mg/kg) and barren lands (13.8 mg/kg) (Table 6). Where “Cd levels in the farming areas tested were lower (range 0.03-0.48 mg/kg) than Tanzania and WHO's upper limit for Cd in agricultural soils. This suggests that, based on these published research findings on Cd buildup in agricultural soils and for environmental quality is lower. More research is needed since Lugwisha (2016) published a study about 6 years ago that suggested there could be significant alterations in Cd accumulation. But also, more studies are required to cover more areas in detail over time to establish spatial-temporal PTEs distribution in topsoils in Tanzania. Additionally, the near mining areas and bare land had Cd concentrations greater than 1 mg/kg, which is the maximum permissible limit in agricultural soils (Table 6). Among 161 samples collected, Cd concentrations were >1 mg/kg (dry weight) in 110 (68.32%) out of 161 samples analyzed and had Cd above Tanzania and USEPA Cd permitted limit in agricultural soils (URT, 2007). Thus,

there is likely to be connected phytotoxicity and health risk to plants, soil biodiversity and soil occupants, and food product contamination because Cd levels determined were higher than allowable concentrations” (Lugwisha, 2016; Mng’ong’o *et al.*, 2021).

**Table 6: Summary of cadmium (Cd) distribution in Tanzanian soils from various land use or cover types**

Land use		Region	Total number of samples		Concentration of Cd (mg Cd/kg dry wt)				Regulatory value Cd Conc>1 mg/kg		Extraction Method	Reference
Code	Description		Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
UAS	Urban agriculture soils	Dar es salaam	24	14.9	0.3	0.4	0.6	0.2	0	0	Aqua regia	Mwegoha and Kihampa 82010)
CR	Cereals (Rice)	Lake zone	18	11.2	0.5	0.5	0.9	0.2	0	0	DTPA	Machiwa (2010)
NMA	Near Mining areas	Singida	26	16.2	7.4	7.6	11.7	1.2	26	100	Aqua regia	Herman and Kihampa (2015)
Veg	Vegetables	Morogoro	9	5.6	0.02	0.03	0.03	0.01	0	0	DTPA	Lugwisha (2016)
BL	Bare land	Ruvuma	84	52.2	13.8	13.8	37.3	6.0	84	100	EDXRF	Banzi <i>et al.</i> (2015)
<b>Total</b>			<b>161</b>	<b>100</b>	<b>4.4</b>	<b>0.48</b>	<b>37.3</b>	<b>1.4</b>	<b>110</b>	<b>68.3</b>		

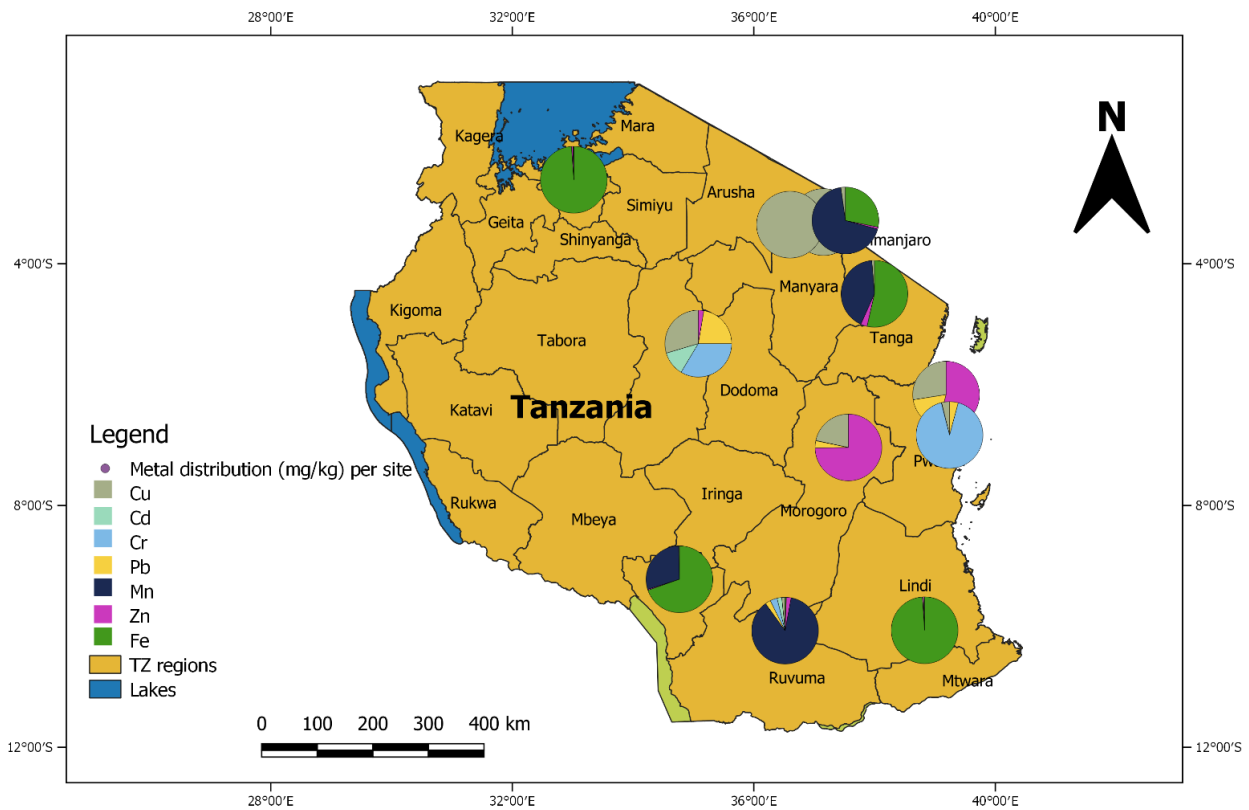
**Table 7: Summary of zinc (Zn) distribution in Tanzanian soils from various land use or cover types**

Land use/cover type		Region	Total number of samples		Concentration of Zn (mg Zn/kg dry wt)				Regulatory value with Zn Conc>5 mg/kg		Extraction Method	References
Code	Description		Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	4.6	59.8	67.2	158.0	41.2	18	100	DTPA	Machiwa (2010)
Mix W	Mixed woodland	Tanga	54	13.8	1.2	2.7	19.6	2.7	21	38.9	DTPA	Meliyo <i>et al.</i> (2015)
CM	Cereals (Maize)	Lindi	20	5.1	75.3	64.5	134.6	42.0	20	100	EDXRF	Koleleni and Mbike (2018)
BL	Bare land	Ruvuma	84	21.4	13.8	13.8	37.3	6.0	84	100	EDXRF	Banzi <i>et al.</i> (2015)
PIC Tea	Permanent industrial crops (tea)	Njombe	24	6.1	0.3	0.2	0.4	0.4	0	0	DTPA	Kitundu and Mrema (2006)
Veg	Vegetables	Morogoro	9	2.3	7.6	1.5	24.8	8.8	7	77.7	DTPA	Lugwisha (2016)
GL	Grassland	Kilimanjaro	50	12.7	2.8	5.6	10.3	2.0	20	40	FTMIRS	Mathew <i>et al.</i> (2016)
IA	Industrial areas	Zanzibar	108	27.5	192.6	67.5	328.9	90.4	108	100	Aqua regia	Mahugija and Sheikh (2018)
NMA	Near Mining areas	Singida	26	6.6	1.3	1.2	2.6	0.5	0	0	Aqua regia	Herman and Kihampa (2015)
<b>Total</b>			<b>393</b>	<b>100</b>	<b>39.4</b>	<b>5.6</b>	<b>328.9</b>	<b>21.6</b>	<b>278</b>	<b>70.74</b>		

**Table 8: Summary of Iron (Fe) distribution in Tanzanian soils from various land use or cover types**

Land use		Region	Total number of samples		Concentration of Fe (mg Fe/kg dry wt)				Sample with Fe Conc>100 mg/kg		Extraction Method	References
Code	Description		Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
Mix W	Mixed woodland	Tanga	54	23.3	65.3	112.5	339.4	86.4	27	50	DTPA	Meliyo <i>et al.</i> (2015)
CM	Cereals (Maize)	Lindi	20	8.6	38427.1	41380.0	28933.7	88820.0	20	100	EDXRF	Koleleni and Mbike (2018)
BL	Bare land	Ruvuma	84	36.2	4.0	3.5	9.1	2.5	0	0	EDXRF	Banzi <i>et al.</i> (2015)
PIC Tea	Permanent industrial crops (tea)	Njombe	24	10.4	43.7	34.4	60.3	5.4	0	0	DTPA	Kitundu and Mrema (2006)
GL	Grassland	Kilimanjaro	50	21.6	130.4	193.4	310.6	49.2	32	64	FTMIRS	Mathew <i>et al.</i> (2016)
<b>Total</b>			<b>232</b>	<b>100</b>	<b>7734.1</b>	<b>112.5</b>	<b>28933.7</b>	<b>17792.7</b>	<b>79</b>	<b>34.1</b>		

**Zinc (Zn) and Iron (Fe):** The concentrations of Fe and Zn in topsoils, as well as their distribution, were found to fluctuate with land use (Table 7 and 8). Maize and paddy growing areas, as well as industrial areas, had higher Fe and Zn concentrations. Where “for example, Lugwisha (2016) and Mahugija and Sheikh (2018), who studied Zn and Fe distribution in topsoils in various parts of Tanzania, found higher Zn values in maize producing areas (75.27), rice farming areas (59.8) and near industrial areas (192.6 mg/kg). While Fe levels were higher (mg/kg) in maize-farming areas (38427.08), grassland (193.43), mixed forest (65.30), and permanent industrial crops (tea) (43.70). the determined Fe values may enhance fixation of plant nutrients, i.e., P, N, S, and Mg hence affecting its availability. Among 393 soil samples studied for Fe and Zn accumulation in topsoils, 278 samples (about 70.74%) had Zn concentrations greater than 5 mg/kg (Table 7), which is the maximum permitted Zn in agricultural soils. Although zinc is a crucial plant nutrient, increased Zn concentrations in soils above 5 mg/kg are likely to impact the availability of other nutrients like Fe and P, as well as cause crop yellowing and wilting due to zinc toxicity. Additionally, higher Zn concentrations in agricultural soils obstruct soil microbial growth and soil activity. Though, maximum allowable limits for Zn varies among countries, but generally are range of 100-200 mg/kg. For instance, China = 200-300 mg/kg, Tanzania = 100 mg/kg, Netherlands = 720 mg/kg, and Canada = 200 mg/kg (CCME, 2007; URT, 2007; USEPA, 1992). Iron (Fe) is essential for plant growth. Nonetheless, high Fe levels in soils can change pH of the soil and affect plant nutrient (e.g., P) availability. In the study of Fe distribution among land use in various regions of Tanzania, 79 soil samples (Table 8) had Fe concentrations beyond the maximum permissible limit of 100 mg/kg in agricultural soils, indicating that there is a risk of P unavailability for plant uptake because of increased P fixation and decline in soil pH. The Fig. 7 depicts a summary of harmful metal distribution in several sites examined in this review section” (Mng’ong’o *et al.*, 2021).



**Figure 7: A simple map depicting the PTEs distribution (ratio) in each study area in Tanzania (Mng'ong'o *et al.*, 2021)**

### 2.11. Metal bioavailability and bioconcentration from soil to plant tissues in agro-ecosystem

Food is the major pathway for PTEs in animal and human bodies via plant uptake from soil through roots and to a less extent, via foliar absorption. However, translocation of PTEs from agricultural soils to plant tissue is complex and hardly predictable; soils with higher levels of PTEs are likely to accelerate PTEs uptake by plants system and grains. But other chemical soil properties like soil texture, soil pH, C/N ratio, and organic carbon may alter PTEs availability, which is primarily transmitted to humans through food, air and water. They enter the food chain mostly through root uptake from agricultural soils and to a small level, through a leaf or foliar intake; PTE transfer from soil to plant is complicated and unpredictable (Agrelli *et al.*, 2017). High levels of metals in farming areas may hasten the uptake of specific PTEs in plant systems and grains, but other physico-chemical soil variables, such as C/N ratio, organic carbon, soil pH, and soil texture, may affect PTEs accessibility to plants (Zhou *et al.*, 2014). Plants typically take PTEs, which are freely available (bioavailable forms). As a result, bioavailability is crucial in determining and predicting PTEs transfer from soil to plants and food systems (Fagnano *et al.*, 2020).

Accumulation of PTEs in soils such as Zn, Cd, and Pb have been found to have a strong positive connection ( $P < 0.01$ ,  $R^2 = 0.95$ ) with PTEs in plant tissues in various investigations (Liu *et al.*, 2015). For that reason, increasing PTEs levels in soils will affect PTEs levels in plant tissues like grains and other edible portions, posing health hazards. However, “some studies indicate that there no or weak correlation between PTEs in agricultural soils and those determined in crop grains as reported by Chanda *et al.* (2011) based on analytical analyses of PTEs in soils and rice grains from paddy farming areas of India. In addition, the study from paddy farming areas in China observed the mean concentrations of Hg (3.0), Cr (72.03), and Pb (38.7 mg/kg) in soils, but Pb and Cr concentrations in paddy rice grain in the same area were lower than detection limit” (Chanda *et al.*, 2011), where the similar scenario was observed by Visconti *et al.* (2019) and Fagnano *et al.* (2020) in Italian soils. Since a certain quantity of PTEs can be unavailable for plant uptake, they are unlikely to infect the food chain, or they are harmless to soil dwellers; bioavailability of PTEs to plants and other soil inhabitants is crucial in assessing adverse consequences. The “bioconcentration (BCF) and translocation factor (TF) of PTEs explain the transfer and bioavailability of PTEs from soil to plant parts and aid in the evaluation of PTEs bioavailability and bioconcentration in the agricultural system” (Lugwisha, 2016). The BCF is calculated by comparing the amount of metal in plant parts/edible portions to the amount of metals in the soils where a specific crop is cultivated (Equation 3), while TF is a ratio of PTEs present in shoots versus PTEs present in plant roots (Equation 4).

$$\text{Bioconcentration Factor (BCF)} = \frac{[M \text{ Plant}]}{[M \text{ soil}]} \quad (3)$$

Where “[M-soil] and [M-plant] are PTEs determined in plants and soil extracts obtained/grown in a particular environment” (Lugwisha, 2016).

$$\text{Translocation factor (TF)} = \frac{[M \text{ Shoot}]}{[M \text{ Roots}]} \quad (4)$$

Where [M-shoot] and [M-root] represent PTEs determined in shoots and roots extracts.

A BCF value of  $>1$  indicates a higher concentration of PTEs in plant tissues than in soil (both expressed on a dry weight basis), whilst a BCF of  $<1$  indicates a PTEs concentration in the soil is above the concentration measured in plants. Based on the study by Lugwisha (2016), BCF values “for Cd, Cu, Pb, and Zn in tomatoes, cauliflower, cabbage, and onion observed in different parts of Morogoro were; at Kihonda were in onion (Cu =7.41, Zn=1.23, and Cr=70.4), Mgeta in tomatoes (Cu=0.19, Cr=6.50, Cd=0.043, and Zn=3.64), and Towelo in cabbages (Cu=24.44, Pb=1.06, Cr=2.21, and Zn=31.73)” (Lugwisha, 2016). Higher BCF thus suggests

that higher PTEs concentrations were in vegetable tissue than in soils, indicating that they may not be suitable for human consumption or posing health risks to consumers. Hence, a thoroughly investigation of the link between PTEs content in soils and crops produced is vital to estimate PTEs bioavailability, bioconcentration and associated health risk needed to establish control options to assure food safety and agro-ecosystem sustainability. However, studies on PTEs translocation and bioconcentration factors in major cereal crops such as paddy rice in Tanzanian agro-ecosystem are currently missing; thus, is a knowledge gap that needs to be addressed.

## **2.12. Environmental risk assessment linked to water eutrophication and metals**

Excessive accumulation of plant nutrients (N and P) and PTEs have detrimental environmental and ecological impacts in agro-ecosystem. Generally, the risk of PTEs accumulation in agro-ecosystem can be determined by potential ecological risk indexes (Li *et al.*, 2019). Usually, sediment fertility and organic carbon are used to estimate the ecological risk through the determination of organic index based on organic carbon and nitrogen (Equation 5).

$$\text{Organic index} = \text{Organic carbon (\%)} \times \text{organic nitrogen in sediment(\%)} \quad (5)$$

Where organic nitrogen (%) is calculated by multiplying total nitrogen (%) by 0.95 because TN is a sum of ammonium-N and organic N (OC-N), where a large fraction is occupied by OC-N (Li *et al.*, 2019). However, this is quite a big generalisation and simplification where the reality the fraction of ON and IN is highly variable, and it is not only ammonium, but also nitrate and nitrite.

An organic index of less than 0.03 indicates oligotrophic; 0.03 to 0.05 mesotrophic, and greater than 0.05 eutrophic (Li *et al.*, 2019); there are little data on the organic index for EAA; therefore, there is a need to have more detailed studies on organic index in EAA which will provide baseline information required for further management practices.

The potential PTEs ecological risk can be estimated by considering the risk index associated with each PTEs in the ecosystem (Equation 6).

$$E_r^i = T_r^i \frac{C^i}{C_n^i} \quad (6)$$

Where " $E_r^i$  is the probable ecological risk coefficient of the  $i^{\text{th}}$  PTEs;  $T_r^i$  is the PTEs toxicity coefficient,  $C^i$  and  $C_n^i$  is PTEs in samples (soil or sediment) and background materials, respectively" (Li *et al.*, 2019).

Studies examining PTEs ecological risk in EAA are rare; nonetheless, few available studies have given more focus on sediments collected from water bodies or farms which are closer to mining areas. No studies have given special attention to agro-ecosystem to estimate the pollution risk linked with and in agro-ecosystem in order to attain United Nations Sustainable Development Goals (SDGs). Olando *et al.* (2020) investigated a variety of metals (Co, Pb, Cr, Fe, Cu, Zn, and Mn) and their sediment  $E_r^i$  in Lake Naivasha (Kenya), which is surrounded by farming areas and found  $E_r^i$  to be; Cu (11.80), Pb (6.50), Co (10.29), Mn (2.86), Cr (1.55), Zn (4.46), and Fe (10.42). The study also discovered that metal toxicity was in the order sequence of  $\text{Cu} > \text{Fe} > \text{Co} > \text{Zn} > \text{Mn} > \text{Cr}$ ; however, all elements had  $E_r^i$  values less than 40 indicating low ecological risk. According to the findings, high PTEs concentration in sediments in lake Naivasha was caused by increased agricultural operations near the lake and increased urbanization in nearby areas. The study by Mungai *et al.* (2016) on  $E_r^i$  of 8 PTEs (Pb, Hg, Ni, Cd, Cu, Zn, As, and Cr) in topsoils in central Kenya stated and established a risk ranking which shown there was more Hg in agricultural soils than other PTEs studied ( $\text{Hg} > \text{Cd} > \text{As} > \text{Cu} > \text{Pb} > \text{Zn} > \text{Ni} > \text{Cr}$ ) and  $E_r^i$  ranged 0.01 to 10.39. Where  $E_r^i$  posed by a single factor was low, except for Cd and Hg, suggesting that Hg and Cd are likely to pose a greater environmental and human risk if not closely monitored. These are among the few studies carried out in East Africa, and further research in agricultural soils is needed to assure long-term land production.

*The comprehensive risk index (RI)* usually indicates that toxicity of PTEs in agro-ecosystem occurs in combinations; thus, estimating the total ecological risk which can be potentially caused by available PTEs is essential. Thus, summation of  $E_r^i$  of individual PTEs provide a comprehensive risk index as determined by Equation 7. The RI is classified as low, moderate, or high, as shown in Table 9.

$$RI = \sum_{i=1}^m E_r^i \quad (7)$$

The RI allows the quantification of PTEs pollution in sediments and soils (Hakanson, 1980). Based on the PTE's toxicity and reactivity to the environment, RI provides a quantifiable number for combined pollution risk to a specific ecological system. The status of pollution and

accompanying dangers are divided into five classes based on RI and  $E_r^i$  index, ranging from low to very high (Table 9).

**Table 9: The summarized level of potential PTEs ecological risk**

Risk Level	Low	Moderate	Considerable	High	Very high
$E_r^i$	<40	40-80	80-160	160-320	>320
RI	<95	95-190	190-380	-	>380

(Hakanson, 1980)

Despite the relevance of RI, “few research studies in East African agro-ecosystem have been conducted. Mungai *et al.* (2016) found that overall ecological risk (RI) of agricultural soils and Lake Naivasha sediments was low (37–61), which was substantially less than Hakanson's RI low-risk estimate of 95 (Table 9). This indicated that PTEs concentrations in soils in research area sat minimal ecological danger to humans and the environment and level of ecological risk posed by a single component was modest. The Hg and Cd, on the other hand, had greater values, indicating that if not carefully handled, this element could constitute a concern to the environment and individuals. Further studies on  $E_r^i$  and RI is needed in soils and sediments from farming areas to establish baseline information required for PTEs monitoring and management for sustainable land and water productivity, to achieve UN SDGs, i.e., Life in land and water, and zero hunger” (Mng’ong’o *et al.*, 2021).

**Total PTEs concentrations:** The total PTEs concentrations determination in sediments and soils from agro-ecosystem and comparing to the established maximum permissible limits, is a simple environmental contamination evaluation indicator since when compared with maximum concentration limits allowed by regulatory authorities in order to protect agricultural soils and water, provide information on contamination status which will be utilized to set out management activities (URT, 2007). In East Africa, number of studies conducted to evaluate PTEs in soils, water, and sediments in residential, industrial, and mining areas (Mahugija & Sheikh, 2018; Mataba *et al.*, 2016), and very few in farming areas (Machiwa, 2010). Therefore, the risks from PTEs contamination in most agricultural soils in East Africa are currently unknown. It is therefore difficult to conclude that agro-ecosystems are safe for humans and livestock as there is a lack of available scientific evidence in agro-ecosystems of Tanzania and neighbouring countries. The lack of this data makes it difficult for management to develop and implement initiatives to prevent additional contamination. As a result, characterizing the concentration of PTEs in soils, water, and sediments from farming regions is a simple and

acceptable environmental evaluation. For instance, a study conducted by Olando *et al.* (2020) determined Co, Zn, Pb, Cu, and Cr concentrations in lake sediments in Eastern Kenya, observed concentrations (mg/kg) of Fe 5,365 (38,851.3–64,938.3), Zn 232.0 (188.0–334.5), Pb 22.1 (14.3–45.9), Cu 33.7 (23.1–46.9), Cr 27.4 (2.5–68.8), and Co 24.1 (17.8–28.8). These higher PTEs values are associated with negative impacts on animal, human, and aquatic animals. Therefore, additional studies are needed, especially which solely focus on agricultural land to ensure higher land productivity, food quality and safety, environmental quality and sustainability.

**PTEs accumulation indicators;** The PTEs accumulation in agricultural soils could be assessed in detail by using different established indicators such as “geochemical-accumulation index (I<sub>geo</sub>), enrichment factor (EF), contamination factor (CF), and pollution load index (PLI)” (Malsiu *et al.*, 2020). The determination of I<sub>geo</sub>, EF, CF, and PLI can help to establish the degree of PTEs accumulation and contamination in agro-ecosystem in detail.

**(i) Contamination factor (CF) and pollution load index (PLI);** The “PLI is estimated as the square root of the multiplication product of CF of each PTEs (Equation 8). The CF is the ratio of PTEs content in the sample and background value in sediment and water samples of the study area (Equation 9). The CF and PLI estimate PTEs contamination. The interpretation of CF is as follows; CF<1 (low pollution), CF 1-3 (moderate pollution), CF 3-6 (high pollution), and CF>6 (very high pollution)” (Gashi *et al.*, 2017).

$$CF (Metals) = \frac{C(metal)}{C(background)} \quad (8)$$

$$PLI = (CF1 \times CF2 \times CF3 \times \dots \times CFn)^{1/n} \quad (9)$$

**(ii) Geoaccumulation index (I<sub>geo</sub>);** The I<sub>geo</sub> provide the degree of PTEs accumulation in the agro-ecosystem and can be calculated as described in equation 10.

$$I_{geo} = \log_2 \left( \frac{C_n}{1.5B_n} \right) \quad (10)$$

Where C<sub>n</sub> is PTEs content, B<sub>n</sub> is the background concentration of respective PTEs, and 1.5 is a lithological changes factor (Gashi *et al.*, 2017). Therefore, I<sub>geo</sub> values interpretation is as follows: “I<sub>geo</sub> ≤ 0, unpolluted; 0 ≤ I<sub>geo</sub> ≤ 1, unpolluted to moderately polluted; 1 ≤ I<sub>geo</sub> ≤ 2, moderately polluted; 2 ≤ I<sub>geo</sub> ≤ 3, moderately to heavily polluted; 3 ≤ I<sub>geo</sub> ≤ 4, heavily polluted; 4 ≤ I<sub>geo</sub> ≤ 5, heavily to extremely polluted; and I<sub>geo</sub> > 5, extremely polluted” (Gashi *et al.*, 2017).

(iii) **Enrichment Factor (EF)**; The accumulation of PTEs from anthropogenic sources in agro-ecosystem can be assessed by determining the EF (Equation 11). Usually, iron (Fe) is selected and considered as a normalizing element for identifying anomalous PTEs contributions due to its abundance (Vemic *et al.*, 2014).

$$EF = \frac{C/Fe(sample)}{C/Fe(background)} \quad (11)$$

Where C/Fe (sample) is ratio of PTEs to Fe in sample and C/Fe (background) is ratio of PTEs to Fe in background sample, generally, EF values are described as: minimal (<2); moderate (2-5); significant (5-20); very high (20-40); and extremely high (>40) enrichment. For most EAA, studies in pollution indices related to PTEs in sediment are scant, while those for agricultural soils are missing. The study by Nkinda *et al.* (2020) determined Igeo, EF, CF, and PLI for Hg, As, Cr, Pb, and Cd in sediments collected in Mara river and Lake Victoria, where found CF <1 during dry period indicating lower level of PTEs contamination, and during the wet period the determined CF were  $1 \leq CF < 3$  which corresponded to moderate contamination level. The determined PLI were above zero but below 1, corresponding to minimal deteriorations. Furthermore, Nkinda *et al.* (2020) reported that determined Igeo were below zero, showing that most of the studied areas were unpolluted due to less geoaccumulation of PTEs; the determined PTEs enrichment (EF) was less than 2 (EF<2), indicating low PTEs enrichment in sediments and soils. Thus, using different pollution or contamination indices can provide a detailed assessment of PTEs accumulation in agro-ecosystem; however, these detailed studies are currently very few in EAA, and where available, they have focused on other ecosystem than agricultural fields.

### 2.13. Levels of N and P in water in agro-ecosystem

The N and P concentrations in still surface water (ponds and lakes) and flowing surface water (rivers and channels) in the natural ecosystem are usually low (<1.0 mg N/L and <0.01 mg P/L), keeping the system stable for freshwater ecosystems. However, agriculture activities reported to increase level of N and P in surface waters, studies conducted by Xu *et al.* (2014) in water quality in farming areas had significantly higher N concentration in agriculture fields (1.5 mg/L) than in conservation areas or forests (1.0 mg/L). The same scenario was observed in flowing surface water, where higher total N (2.4 mg/L) were determined in agricultural fields than conservation and forest areas (0.5 mg/L). This indicates that agricultural activities are potential contributors of N and P to surface waters, disrupting ecology. In countries like China

and United States, concentrations of total N in surface water have been classified to control water eutrophication and improve water quality. To ensure water quality, according to USEPA (USEPA, 1992), the level of N should not exceed 0.3 mg/L in flowing water (streams and rivers) and 0.1 mg/L in still reservoirs (lakes and ponds) and for P should not exceed 0.1 mg/L (Xu *et al.*, 2014). Based on the Chinese national quality standards guideline for surface water has classified surface water into five classes based on N and P concentration (Table 10) where class I-III can be used for domestic use (drinking) while class IV–V is used for industrial and agricultural uses only (Guo *et al.*, 2020; Xu *et al.*, 2014).

**Table 10: Total N and P concentration in I-V water classes as classified by Chinese national quality standards for surface water**

Element Concentration (mg/L)	Class ID				
	I	II	III	IV	V
N	<0.2	0.2 - 0.5	0.5 -1.0	1.0 -1.5	1.5 – 2.0
P	<0.02	0.1 (0.025)	0.2 (0.05)	0.2	0.2

*Values in brackets are for P concentration in lakes and other reservoirs where water is standing still or has restricted movement.*

However, few studies have been conducted on N and P concentration in East Africa agro-ecosystem; the concentration of N and P in stream waters has been increasing since the 1980s due to increased industrial, agricultural intensification and mining activities (Sitoki *et al.*, 2010). Studies in irrigation water quality in Kapunga rice farm in Southern Highland Tanzania reported more than 2.5 mg/L of N in some drainage channels and paddy fields, indicating N enrichment from paddy farming areas (FBD, 2007; Mutayoba *et al.*, 2018b, 2018a). Also, studies by Mshana (2015) on water qualities in Lake Rukwa observed an appreciable amount of N, P, and Hg in water and sediment as influenced by agricultural intensification and mining activities around the lake. Studies in Lake Victoria reported increased levels of N and P in the range of 16.2 to 87.9 µg/L and 39.6-92 µg/L, respectively (Gikuma-Njuru *et al.*, 2017a). The point and non-point sources are contributors of N and P to surface waters; however, a point source is well controlled and monitored, however, the some cities in EA have direct sewage input into the streams with no water treatment nor monitoring and the point sources can thus also be major inputs of N and P to streams, especially in urbanized areas, but their proportion compared to previous years has significantly reduced. Thus, non-point sources, especially from agriculture activities, are the primary source of N and P to water bodies in agro-ecosystem nowadays. Despite the importance of this information in water quality management, this

information is currently limited in most East-Africa countries' agro-ecosystem, more research studies are needed to measure levels of N and P in water in streams and ponds in farming areas and to develop management strategies to ensure safe and sustainable water use in agro-ecosystem.

#### **2.14. Paddy farming and eutrophication**

Irrigation paddy farming receives special attention on water eutrophication in agro-ecosystem due to the nature of farming itself; generally, paddy farming requires a large amount of water to enter paddy fields throughout the growing period. Therefore, nutrient loss from paddy farms is high and contributes to water contamination and eutrophication of the freshwater ecosystem (Krupa *et al.*, 2011; Xu *et al.*, 2014). In addition, most paddy farms are located in areas with strong hydrological connections and networks with surface and groundwater; therefore, the risk of nutrient enrichment from paddy farms to water bodies is high (Kashaigili *et al.*, 2006; Mutayoba *et al.*, 2018a). In China, India, Indonesia and Bangladesh, which are the leading paddy rice producers, water quality concerns have been reported in paddy farming areas due to intensive use of fertilizer and water (Krupa *et al.*, 2011) and the same scenario is of concern for East African agro-ecosystems. In intensive and commercial paddy farming areas, soil fertility management is conducted solely by adding organic and inorganic fertilizers such as DAP, NPK, CAN, TSP and manure for basal and top dressing. Because flooding system of irrigation commonly used in paddy farming in East Africa allows more water in paddy fields than plant requirements and more water overflows from rice fields to rivers or main drainage channels. The overflows from paddy fields usually are enriched with nutrients such as P and N loading to water bodies leading to eutrophication (Krupa *et al.*, 2011). For example, studies by Forest and Bee Division (2007) in Usangu basin in paddy farming and rivers in Mbeya region reported increased content of K (11.3 mg/L), Ca (11.1 mg/L), Mn (0.01 mg/L), Fe (0.81 mg/L) and micronutrients in water samples as the result of agrochemical use in paddy farming areas. Since in Sub-Saharan Africa, the nutrient enrichment from paddy farms is more significant, increasing the eutrophication problem (Jian *et al.*, 2016). The use of treated/partially treated wastewater in paddy farming is also a potential source of nutrients to plants but also a potential source of pollutants in water such as PTEs and organic pollutants (e.g., organochlorine pesticides). In Sub-Saharan Africa, few studies about influence of paddy farming on water quality and eutrophication through N and P loss have been conducted; hence more studies are needed to estimate the influence of paddy farming on water quality and sustainability of agro-

ecosystem. But also the other driver of nutrient fluxes in paddy farms such as flooding of the farms which tend to change the redox concentrations. There is generally less oxygen and lower pH in the flooded paddy systems. Where in the reduced form, Fe, Al and Ca have a lower capacity to bind P (and other nutrients), thus making them to be more easily flushed out of the system through surface runoffs, leaching and soil erosion.

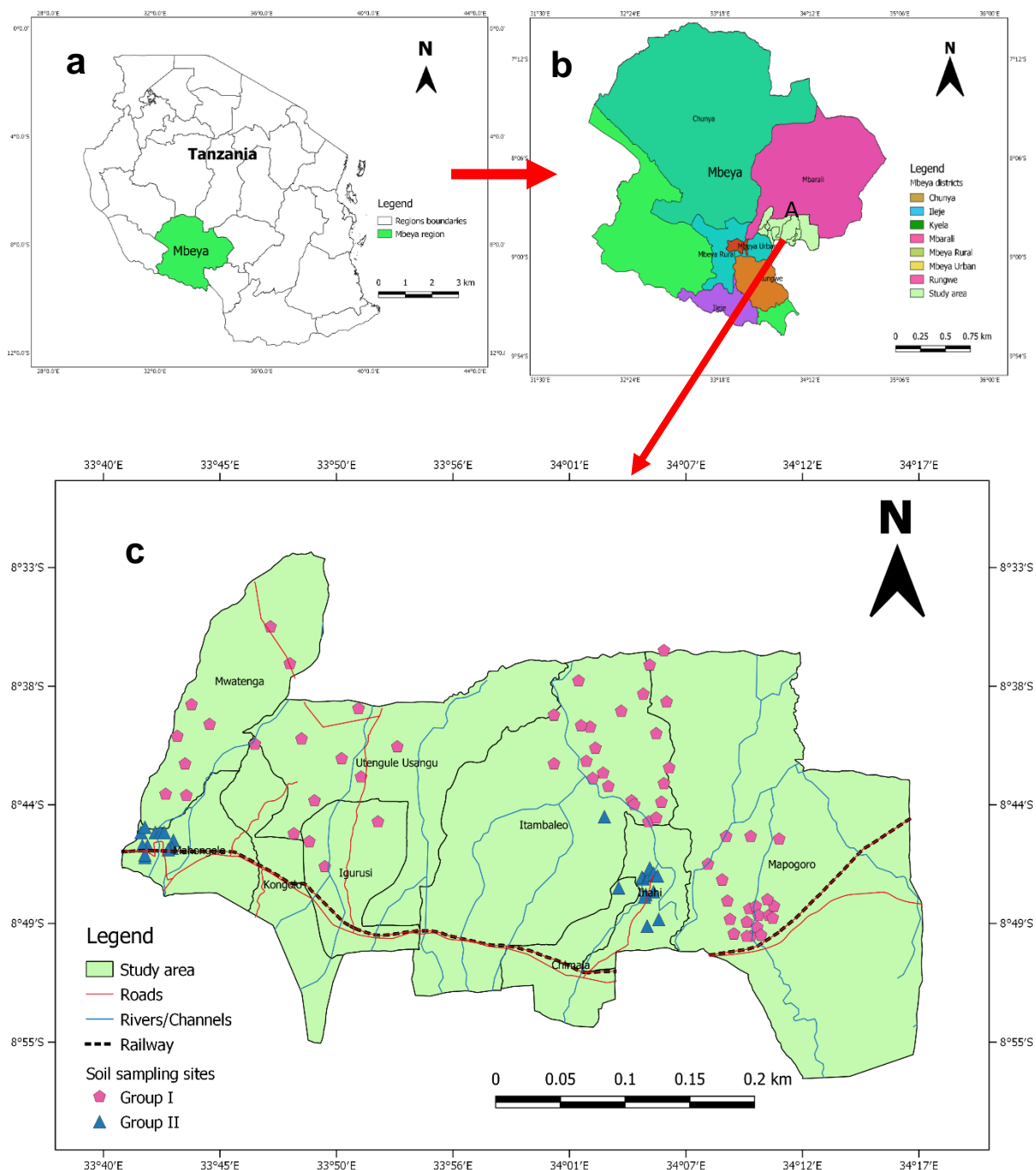
## CHAPTER THREE

### MATERIALS AND METHODS

#### 3.1. Study area description

This study was conducted in Usangu Basin (USB), in Mbarali district, Mbeya region in Southern Highland Tanzania (SHT). Geographically USB is located between latitudes 7°4' and 9°25' South and longitudes 33°40' and 35°40' East. Usangu basin (USB) forms the upper part of the Rufiji River basin (Fig. 8). Generally, USB is the flood plain that receives river water and runoffs from Udzungwa and Kipengele mountain ranges; the area receives water runoffs from the growing towns along TAZAM (Tanzania and Zambia Highway) and TAZARA (Tanzania and Zambia Railway) line and Mbeya city. The Usangu basin has extensive river networks, including eight main rivers (such as little Ruaha, Kimani, Mkoji, Mbarali, Ripera, Ndembera, and Chimala rivers), which feed the plain utilized in irrigated paddy rice farming and horticultural crop production. Thus, supporting many irrigation schemes in the mid and lowlands. In addition, water in the lowlands supports wildlife in Ihefu and Ruaha national park. The Usangu basin covers an area of approximately 20 800 km<sup>2</sup> (Fox, 2004; Kashaigili *et al.*, 2006). Geologically, the basin has volcanic soil materials and fluvial soils, starting from Chimala escapement, which marks as abounding of the basin in the north. In the northern, it is a plain itself. The Usangu basin is divided into three parts:

(i) The Upper Usangu (UPS), which is characterized by mountainous and undulating slopes; this area is where the TAZAM and TAZARA pass, and it has been associated with dramatic increasing settlement, urbanization, and industrialization. The area has small to medium processing industries; along this area (UPS), some mining activities of common minerals such as gravel, sand, calcites, and previous artisanal gold mining existed (for example, at Igalako and Mabadaga). In the far upper of this area is the mountainous part, which is a national reserved area which is under TANAPA (Tanzania National Parks). All rivers and drainage channels from Kipengele and Poroto mountains and runoffs from cities and towns of Mbeya pass through UPS to the middle and lower part of the USB.



**Figure 8: The study area map showing the soil sampling among irrigation schemes within Group I (pure agriculture schemes) or II (mixed agriculture schemes) areas within the Usangu basin-Mbeya Region, Tanzania**

(ii) The middle part of Usangu basin (MPS) is composed of a wide flat plain with fluvial soils materials with frequent flooding during the rainy season (December to March). The area receives water from all rivers and seasonal rivers, which transport surface water runoffs from the upper part of the basin. The area is dominated by small and large irrigation farms where paddy rice, potatoes, maize, and horticultural crops are mainly grown. In this part, water from rivers and drainage channels from UPS is utilized in paddy farming, where water is diverted

from rivers to farms using constructed irrigation channels (paved and unpaved). In this area, water ponding in agricultural fields, especially paddy fields, is about 10-25 cm depth during the entire cropping season (December to May). This is possible because MPS act as a flood plain receiving river and surface runoff water from UPS, causing a constant flow of water over paddy fields to downstream. Due to the fact that this water is flowing through agricultural fields, likely to accumulate and transport plant nutrients and other agrochemicals residuals downstream. To facilitate field activities in the area and due to high land productivity potential, there is increasing scattered settlement in the area leading to urbanization, which might interfere with agro-ecosystem productivity and sustainability.

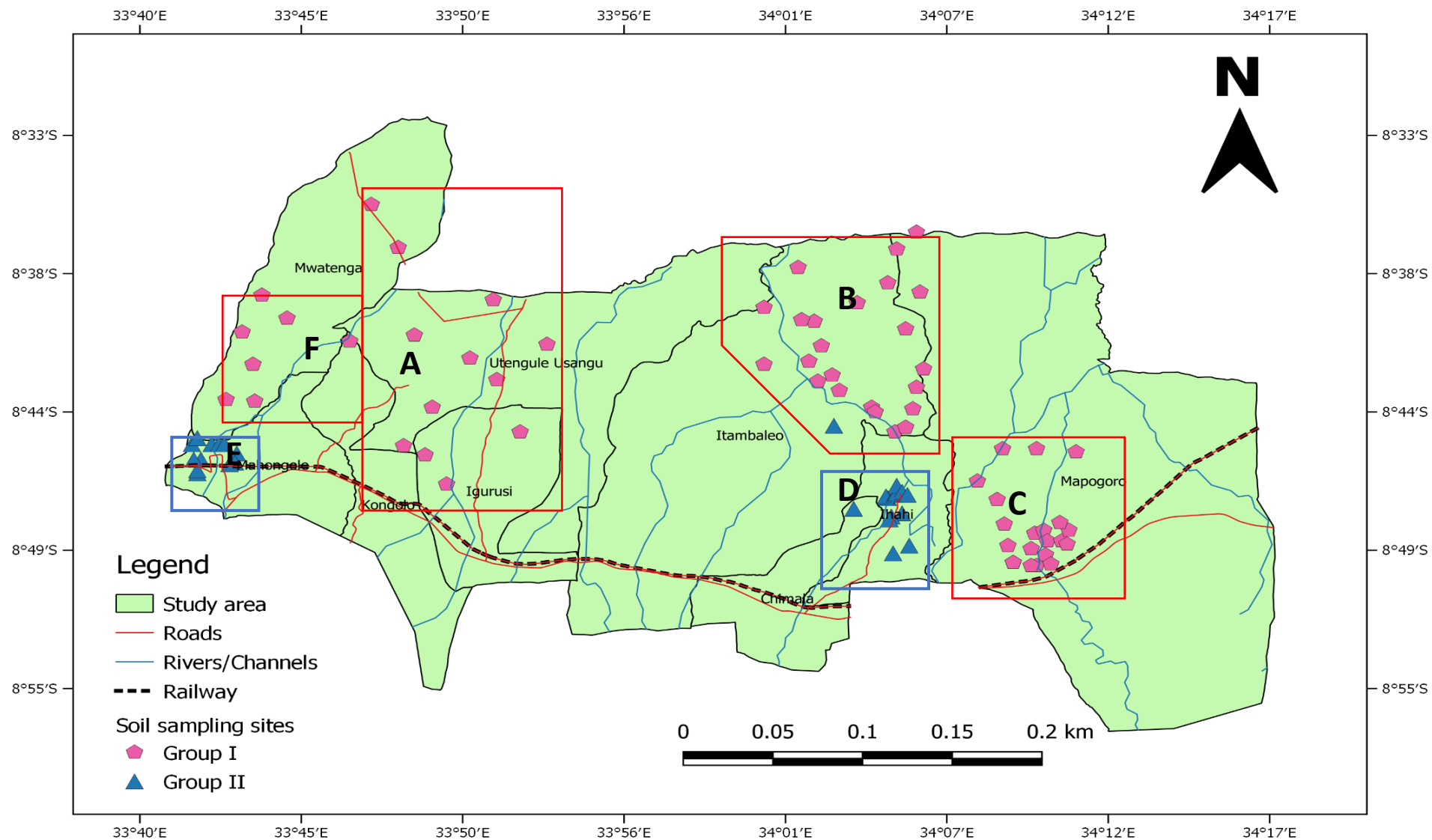
(iii) The downstream part of USB (DPS): The downstream part of the Usangu catchment converges to create narrow natural basins forming a Great Ruaha River network that flows to Mtera and Kidatu dams, which contributes over 40% of electric power in the national grid (Kadigi *et al.*, 2003). The downstream parts also host wildlife conservation areas such as Ruaha National Park and other Madibira, Idodi, and Iringa rural towns. The community and inhabitants sustainability in DPS are directly influenced by activity happening in the UPS and MPS basin as it drives water flow, quality and soil and water contaminants.

The hilly southern part of the basin has an annual precipitation range from 1 000 to 1 600 mm. In the northern part, USB is characterized by an extensive wide flat plan predominated by alluvial soils observed to affirm settlement, both irrigation and dryland farming, which receives an annual rainfall of less than 700 mm, necessitates supplemental irrigation, is needed to grow crops (Kadigi *et al.*, 2003). In general, Usangu basin has unimodal rainfall patterns and obtains rainfall from December to March and experiences dryness for seven months from April to November. Usangu basin is famous for paddy production and produces more than 30% of paddy rice consumed in Southern Highland Tanzania and about 14% of rice consumed in Tanzania. The southern part of the Usangu basin has a number of rivers and slopes that drain river, rainfall, and surface water runoff to northern part of the basin. This water is utilized in irrigation paddy farming, and the rest is allowed to drain down to Great Ruaha River, crossing Ruaha National Park to Mtera and Kidatu dams (Fig. 8).

This study was conducted in ten irrigation schemes within the Usangu basin or Usangu agro-ecosystem; the scheme included in this study were Chimala, Mahongole, Ihahi, Igalako, Ilaji, Uturo, Kapunga, Mubuyuni, Mabadaga, and Isenyela. These irrigation schemes in the study area were classified into two major groups depending on the management and level of

intensification (Appendix 14). The two groups were “(i) **Group I:-purely agriculture (pure agriculture schemes)** where there are only farms and no residential/settlements such as A-Utengule usangu, B-Kapunga, C-Mubuyuni, Uturo, Isenyela and Mabadaga and F-Mwatenga (Fig. 9); Schemes in Group I have well-established irrigation systems with paved irrigation channels. These schemes are highly mechanized and intensified for high yields, with increased use of inorganic fertilizer, pesticides, and herbicides” (Carvalho, 2015; Ngailo *et al.*, 2016). “(ii) **Group II:-mixed agriculture schemes** include farming areas and scattered rural settlements (such as D-Ihahi and-Chimala, E-Igalako and Mahongole) (Fig. 9). The group II schemes are situated in farming areas and scattered rural/town settlements in between, which can likely positively or negatively influence PTEs concentration and distribution in agricultural soils. The area mainly involves smallholder farmers with less agrochemical utilization; where organic manure and inorganic fertilizer application are commonly used soil fertility management strategies” (Mng’ong’o *et al.*, 2021; Ngailo *et al.*, 2016).

The “flooding irrigation system is used in both schemes groups to allow water to enter paddy fields and ponds, resulting in a water depth of more than 15 cm or up to 25 cm. Excess water flows back into the main river or canal, which is occasionally supplemented with pesticide residues (FBD, 2007). Furthermore, due to waste disposals from home and urban effluents, settlements in the area may influence soil quality. As a result, the scheme type can have an impact on PTEs concentration and dispersion in agricultural soils (Kibassa *et al.*, 2013; Shemdoe, 2010). In each group in the study area, there are areas reserved (non-cultivated areas (over 15 years) here termed as conservation areas) where less/no anthropogenic activities conducted, and these areas include community managed forests” (Mng’ong’o *et al.*, 2021).



**Figure 9: Scheme classification based on land use where scheme A, B, C and F are predominantly pure agriculture (Group I) while D and E are mixed agriculture (Group II)**

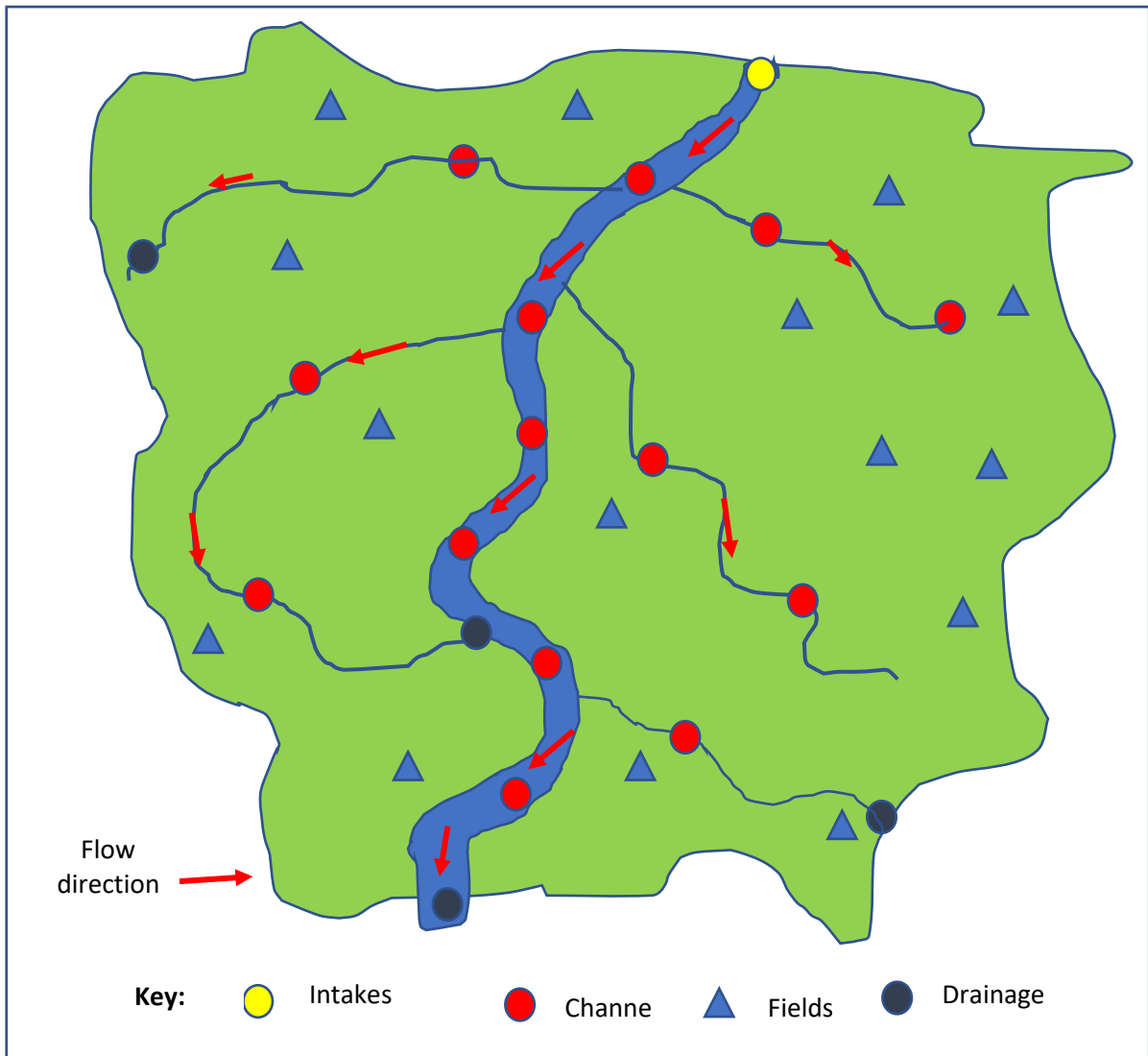
### 3.2. The study design and sample collection

To ensure good representation of the study area of Usangu agro-ecosystem (UA), a stratified sampling design was used, where the study area was divided into different strata based on the land use, terrain, drainage and landscape in different elevations zones. The study area was divided into 10 irrigation zones with three land use type per zone (maize farming, paddy farming and conservation areas (uncultivated land for over 15 years)). A stratified random sampling of soils, water, sediments, and plants was conducted within each stratum and land use (Fig. 8 and 9). Ten irrigation schemes considered in this study were Kapunga, Mubuyuni, Uturo, Ihahi, Chimala, Isenyela, Mabadaga, Mahongole, Igalako and Ilaji. These are major irrigation schemes in the upper Usangu basin and are potential for paddy farming and other cereal crop production. In each site, soil, water, sediment, and plant samples were collected from November 2019 to April 2020 and June 2020 to August 2021. In addition, earthworm surveys were conducted in August 2021 to determine the soil health proxies in UA as influenced by the current land use.

**Soil sampling:** For soil sampling, three points from the centre of each selected sampling point in the perimeter of three meters (in Y design) were sampled and composited to make one soil sample (composite sample). In each selected sampling point, three samples were taken at a depth of 0-30 cm, which is a common and standard plough layer in UA. Approximately 1000 grams of soil were collected using a handheld auger; the collected soil samples were stored in plastic zipper bags and transported to the soil science laboratory of Tanzania agricultural research institute (TARI) Uyole for air drying and other sample preparation activities. After initial basic sample preparation, soil samples were transported to the laboratory of Life Sciences and Bioengineering at Nelson Mandela African Institution of Science and Technology Arusha-Tanzania for further processing for analytical analysis. The collected soil samples were air-dried in a cool, dry place until a constant weight was achieved; the dried soil were grounded by a wooden stick and sieved by a plastic sieve to pass a <2 mm sieve to get the fine earth required for different parameter analyses. From the fine earth (<2 mm), about 100 grams of dried soil samples were taken and stored in plastic bags ready for physical and chemical analysis.

**Water Sampling:** Water samples were collected from rivers, channels, and water canals before entering the paddy farms (at the mouth), in paddy farms and after leaving the paddy farms (at the exit). In detail, water samples were taken from four sections in each irrigation scheme such

as **intakes, channels, in fields and drainages** (Fig. 10) from November to December 2019 and May to June 2021. The description of water samples collected were: **Intakes** are water samples collected from entry points or sources of rivers where there were little anthropogenic activities; this point is the starting point of irrigation channels directing water to paddy fields; **Channels** were water samples from main irrigation channels in paddy plantations; **Fields** were water samples collected inside paddy fields, and **Drainages** were water samples collected at exits of irrigation channels containing water which has been utilized in fields then draining back to main channels or river, and this is important for water quality of the other ecosystem connected to farming areas, but also to analyze the potential loss of nutrients from agricultural fields to water bodies which can potentially leads to lower yields. Before water sampling, the sampling containers were washed with 10% nitric acid and rinsed twice with distilled water and allowed to dry. During sampling day, the sampling bottle was rinsed with water from the sampling point three times, where water were taken by 500 ml plastic cup and added to the sampling bottle until full and discarded three times; then, after three times of rinsing, water sample for analysis were taken. Water was added to the sampling container through <1 mm plastic sieve out bigger organic materials and to avoid the collection of soil and sediment particles along with water. About 500 ml of water were sampled and stored in an acid-washed plastic bottle at 4°C until analysis.



**Figure 10: Schematic of water sampling design: (i) Intakes (water before entering paddy fields), (ii) Channels (water entered schemes but still in main channels), (iii) Fields (water is in paddy fields), (iv) Drainages (water leaving paddy fields to the main river or water ponds)**

**Sediment sampling:** For sediments, to analyze the required soil nutrients and PTEs parameters in river, channels and drainage channels, deposited sediment were collected at the bottom of the rivers and channels using a 300 ml cup attached to a long stick. Before sampling, the cup was rinsed with water from the particular sampling site three times. Then were sent deep into the channel or river, and approximately 500 grams of wet sediment were scooped out and placed into a clean 500 ml container and tied with its cover. The collected wet sediment samples were transported to the laboratory and dried in the oven at 60°C until constant weight and then was ground by bow mill (grinding machine) to pass less than 0.1 mm plastic sieve. The fine grounded dried sediment was stored in paper bags at room temperature until analyses.

**For plant samples;** Sampling of plant samples were conducted, including paddy rice as a major crop in UA for plant nutrients and PTEs analysis. Plants samples were collected from six irrigation schemes within the study area. The irrigation scheme involved in plant sampling were Kapunga, Igalako, Uturo, Mubuyuni, Ihahi, and Mahongole. These schemes represent major irrigated paddy rice producers in UA. “It has well-established irrigation systems and is highly mechanized and intensified for high yields, with high inorganic fertilizer use such as NPK, CAN, DAP, TSP, and SA” (Ngailo *et al.*, 2016). The flooding irrigation system is common in paddy farming areas where water is allowed to enter fields, creating a water depth of more than 15 cm (some times up to 25 cm) in paddy fields, and later allowed to return to the main river or channel, which from time to time are associated with agrochemical residuals (FBD, 2007; Kibassa *et al.*, 2013; Mwegoha & Kihampa, 2010; Shemdoe, 2010). Plant samples were collected from November 2019 to April 2020 and May to June 2021, where the whole plant (grains, straws, and roots) samples were collected; 14 plant samples were collected in each scheme making a total of 84 plant samples. The plant samples were separated into grains (unpolished grains), straws, and roots, then dried in an oven until stable weight and ground to pass a 2 mm sieve for further analyses.

**Earthworm survey:** Earthworm surveys were conducted in August 2021 to determine the distribution and diversity of earthworms in UA. The survey were conducted as follows: for each site, a 35 cm × 35 cm quadrat were used and were randomly placed at each sampling point; then carefully, the soil were excavated to 50 cm depth and spread to the plastic mat to capture and handpick the surface and deep-surface earthworm dwellers (Mcinga *et al.*, 2021). From the collected earthworms, the fresh weight of the sampled earthworms were recorded to the nearest 0.01 gram. After recording the fresh weight of the earthworms, the collected earthworms were euthanised in 70% ethanol and stored for later classification using the dichotomous key for earthworm identification (NRRI, 2011). The discover life guide for earthworm identification (Discover Life Organisation 2016) were also used to aid in identifying earthworms that could not be identified with the dichotomous key. Earthworms were then dried at 60°C for a minimum of 24 hours to constant weight to measure their dry biomass. After dry weighing, the dried earthworms were placed in a muffle furnace at 500°C for approximately 5 hours to burn off all the combustible parts to determine “ash-free-dry-biomass” (NRRI 2011). In this study, ash-free dry biomass was used as the final earthworm measure. The ash-free dry biomass of the earthworms was then calculated by subtracting the ash contents of the

earthworm from the dry weight. The diversity index (H) and species evenness (E) were also determined as per the methods described by Mcinga *et al.* (2021).

For field soil quality assessment and references, some soil samples were collected from conservation areas (non-cultivated areas) to understand the impacts of anthropogenic activities in agro-ecosystem on the health of essential soil invertebrates' abundance, such as earthworms as ecosystem engineers. The conservation areas involved in this study included community managed forests where there are less anthropogenic activities. Soil and water samples were collected in these areas and used as the reference or baseline information for the natural state of soils and waters. Furthermore, PTEs and soil nutrient status (fertility (N and P)) data from previous studies in the UA were obtained from published papers and reports to save as reference or baseline information; however, this information is scanty in the study area. To estimate the flow of P, N and PTEs in the landscape gradient (elevation), the study was carried out across and along elevation gradients ranging from 985 to 2312 meters above sea level along the South-North facing slope of Usangu basin. The distance between sampling points in each gradient and scheme were at least 100 meters.

### **3.3. A detailed summary of materials and methods for each research objective**

#### **3.3.1. Objective 1: To determine the current soil fertility status in UA**

**Sample collection and preparation:** The soils were sampled at depths of 0-30 cm from ten irrigation schemes in three land uses (conservation areas, maize and paddy farming areas); the collected soil samples were air-dried under drying shade until constant weight and then grinded and sieved to pass through a 2 mm plastic sieve as described in detail in section 3.2.

**Analytical procedures:** The total P and total dissolved P (available P) were determined by Mehlich 3 method as described in Pierzynski (2000). In addition, determination of other soil fertility parameters were conducted alongside determination of soil phosphate status. Where, “determination of Ca, K, S, Al, Mg, and micronutrients such as Zn, Mn, Cu, Fe, Co, Ni, and Cr, were determined by Mehlich 3 method (M3); which extracts readily available plant nutrients, both macro, and micronutrients”. In summary, “Mehlich 3 extraction method (M3), which is a mixture of acetic acid (0.2 M CH<sub>3</sub>COOH), nitric acid (0.013 M HNO<sub>3</sub>), ammonium nitrate (0.25 M NH<sub>4</sub>NO<sub>3</sub>), ammonium fluoride (0.015 M NH<sub>4</sub>F) and ethylenediaminetetraacetic acid (0.001M EDTA) were used” (Mehlich, 1984).

Where, “2 grams of fine air-dried soils samples weighed into 50 ml centrifuge tubes, 20 ml of M3 were added and tied, shaken for five minutes in a mechanical shaker, at 180 rpm at room temperature (20°C). Next, the mixture centrifuged at 1200 rpm for 5 minutes and filtered into a 10 ml volumetric flask through an acid-resistant membrane filter (0.42 µm Whatman No. 42) to obtain clear filtrates, all samples were extracted and analyzed in triplicate. The standards solutions were made from a 1000 mg/L stock solution by a series of dilutions. The Al, Mg, P, Ca, Fe, and micronutrient concentrations in M3 soil extracts were measured by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Thermo Scientific iCAP 7400 ICP-OES Pickles) and Inductively Coupled Plasma Mass Spectrophotometer (ICP-MS, Thermo Scientific iCAP TQ MS Ermentrude)” (Mng’ong’o *et al.*, 2021).

The pH of soil samples was determined using Chaturvedi and Sankar (2006) glass electrode method (pH meter), with a water-to-soil ratio of 1:2.5 (soil/H<sub>2</sub>O). Where “10 grams of soil sample were weighed into 50 ml beaker and mixed with 20 ml of distilled water. Then the soil were allowed to dissolve in distilled water without stirring; then the mixture were stirred thoroughly for 10 seconds using a glass rod. Furthermore, the suspension were stirred for additional 30 minutes. After 30 minutes, soil pH were determined by calibrated pH meter. The pH meter was calibrated using two buffer solutions, the neutral pH (7.0) and the other was chosen based on the range of pH in the soil. Where buffer solutions were kept in the beakers, and electrodes were inserted alternately in beakers containing the two buffer solutions and adjusted the pH” (Chaturvedi & Sankar, 2006).

The chromic acid titration method of Walkley and Black was used in determination of organic carbon (SOC) amount in the soil (McLeod, 1973). For Mehlich 3 extractable elements, the instrumental and technique detection limits (LOD) were determined. Using a 1000 mg/L stock solution, where multiple dilutions were utilized to prepare standards solution for various elements.

The characterization of soil types in the study area based on a world reference base were conducted, where based on the observed soil characteristics and chemical determined soil parameters were feeded and referred to FAO world reference base database to determine major soil types. The common major soil types found in the study are were umbric nitisols, haplic lixisols, haplic acrisols, eutric fluvisols, and eutric leptosols (Fig. 11) (FAO, 2014; Wickama & Mowo, 2001).

### **3.3.2. Objective 2: To establish soil phosphate sorption capacity (PSC) and phosphate saturation degree (PSD) indicators as a check for estimating risk of P fixations and desorption**

**Sample collection and preparation:** From the collected soils and which were prepared as described in Section 3.2, were used for analysis and determination of phosphate sorption capacity (PSC), phosphate saturation degree (PSD), P loss and maximum amount of P that can be adsorbed in soil colloids, and sorption and desorption experiment.

**Analytical procedures:** The analyzes of inherent P, soil organic carbon (OC), clay content, Al-, Ca-, and Fe-hydroxides were conducted to determine PSC, PSD, P loss and maximum P adsorption. The amount of amorphous or non-crystalline Al-, Fe-, Ca (hydr) oxides (Al Fe, and Ca, respectively) were determined by Mehlich 3 method (Mehlich, 1984), which has a high correlation with the ammonium-oxalate extraction method a commonly used method for PSC and PSD studies (Kleinman & Sharpley, 2002). The soil organic carbon (SOC) content was determined by Walkley and Black chromic acid titration method (McLeod, 1973). The initial P mineral-bound ( $P_{M3}$ ) and Mehlich 3 extractable Al, Fe, Mg and Ca (in mmol/kg) were estimated as the requirement for the determination of PSC and PSD. From 100-gram air-dried collected soil samples, extractable  $P_{M3}$ ,  $Al_{M3}$ ,  $Fe_{M3}$ , and  $Ca_{M3}$ , were determined by M3 as follows.

In summary, “about 2 grams of fine air-dried soils samples weighed into 50 ml centrifuge tubes, then 20 ml of M3 extraction solution added, and knotted, and shaken for 5 minutes at 180 rpm in a mechanical shaker, later centrifuged at 1200 rpm for 5 minutes before being filtered by an acid-resistant filter (Whatman No. 42) with a 0.42  $\mu$ m pore size into a 15 ml volumetric flask to get clean filtrates. The Mehlich 3 extraction solution was used to make the soil extracts to the mark, and all samples were extracted and analyzed in triplicate. To control the determination quality of the method used, in each batch, three blanks were prepared in the same manner as soil sample; however, centrifuge tubes of blanks did not contain soil samples (Appendix 4). For the determination of the concentration of Mg, P, Fe, Ca, Al, and micronutrients in soil extract, standards of respective elements were prepared from 1000 mg/L Lab king stock solution by serial dilutions. The Ca, P, Fe, Mg, Al, and micronutrients concentration in M3 soil extracts were analyzed by ICP-MS (Thermo Scientific iCAP TQ MS Ermentrude) and ICP-OES (Thermo Scientific iCAP 7400 ICP-OES Pickles)” (Mng’ong’o *et al.*, 2021).

**Quality assurance:** To guarantee data reliability and to avoid any potential error that can be due to external factors, the certified reference materials (CRM) such as “SCP (S150123029) EnvironMAT) from SCP Science-Qmx laboratories-UK, were employed to monitor determination quality of obtained data” (Mng’ong’o *et al.*, 2021). The recovery of samples spiked with standards were observed to range from 86% to 104.1%, indicating better determination quality and reliability of the obtained data for future reproducibility. In addition, reagents blanks were used following the same procedures applied to soil samples, except no samples were included. Furthermore, all reagents and chemicals used were of analytical grade and were used without further purifications. Moreover, all glassware used in the experiments were washed with dilute 10% nitric acid (HNO<sub>3</sub>) and 10% hydrochloric acid (HCl), followed by four times rinsing with distilled water and finally were rinsed thrice with Milli-Q water (>18.2 mΩ/cm) to avoid any possible traces of contamination. Moreover, all the reagents and calibration standards were prepared using milli-Q water (>18.2 mΩ/cm). The detection limits (LOD) for instrumental and method used for the determination of M3 extractable elements studied are summarized in Table 11.

**Table 11: Summary of detection limits (LODs in mg/L) for instrument and method for selected plant nutrients in certified reference material (SCP EnviroMAT (S150123029)) using Mehlich 3 method (M3)**

Element	Instrumental LOD	Method LOD	SCP-experimental values	SCP-reference values
			mg/L	
Ca	0.031	0.032	0.402	0.407
Mg	0.005	0.006	0.039	0.045
Al	0.001	0.021	0.069	0.102
Mn	0.002	0.003	0.005	0.006
Fe	0.050	0.050	0.026	0.031
P	0.106	0.120	0.020	0.026
Zn	0.010	0.010	0.042	0.044

Traditionally, PSC and PSD of agricultural soils have been estimated using data from ammonium oxalate studies, which determine extractable Ca, Al, P, and Fe contents (Kleinman & Sharpley, 2002). Nevertheless, most soil laboratories do not do ammonium oxalate analysis as part of their standard or routine procedures; therefore, its application is limited (Kleinman,

2017; Kleinman & Sharpley, 2002). On the other hand, the Mehlich 3 approach, which was established in United States in 1984 by Donald Mehlich (Mehlich, 1984), is widely employed in most soil laboratories as a routine and standard procedure for estimating soil fertility parameters; thus, Mehlich 3 data are easily available in most laboratories. The study by Kleinman and Sharpley (2002) found a high correlation ( $R^2 > 0.96\%$ ) between PSC and PSD assessed by ammonium oxalate and Mehlich 3 method (M3) in diverse agricultural soil types. As a result, it was determined that PSC and PSD may be estimated using M3 data, which are normally available in most soil science laboratories, to reduce environmental waste, serve time, and money. As a result, the M3 data, which are easily determined and readily available, were utilized to estimate  $PSC_{M3}$  and  $PSD_{M3}$  in UA for agricultural and environmental conservation reasons. The “ $PSC_{M3}$  and  $PSD_{M3}$  (Fe+Al+Ca) are more useful as M3 extraction is widely used in soil testing laboratories to predict plant-available P, Al, Fe, and other elements, but also used to predict the risk of P loss from agricultural fields” (Kleinman & Sharpley, 2002).

The phosphate sorption capacity (PSC) of the soil studied were determined based on inherent P, Al, Ca, and Fe concentration; these are the main determinants of PSC (Equation 12 and 13), while PSD was calculated and determined based on PSC and inherent P of the soils (Equation 14 and 15). In acidic soils, non-crystalline Al and Fe minerals control PSC (Equation 12), while in calcareous soils, Ca is a key determinant of soil PSC (Equation 13).

$$PSC_{M3(Fe+Al)} = (Fe_{M3} + Al_{M3}) \quad (12)$$

$$PSC_{M3(Ca)} = (Ca_{M3}) \quad (13)$$

Where “PSC is a soil P sorption capacity (in mmol/kg) of the soil colloids,  $Fe_{M3}$ ,  $Ca_{M3}$ , and  $Al_{M3}$  is M3 extractable Fe, Al and Ca (in mmol/kg)” (Kleinman & Sharpley, 2002).

The PSD in agricultural soils were determined based on the mean  $P_{M3}$  and mean PSC ( $Al_{M3}$ ,  $Ca_{M3}$ , and  $Fe_{M3}$ ) as described by Kleinman and Sharpley (2002). Where “in non-calcareous soils (pH<8), the PSD was determined based on Mehlich-3 P ( $P_{M3}$ ), iron ( $Fe_{M3}$ ), and aluminium ( $Al_{M3}$ ) (Equation 14) and in alkaline soils with pH greater than 8, PSD were estimated from Mehlich-3 P ( $P_{M3}$ ) and calcium ( $Ca_{M3}$ )” (Equation 15).

$$PSD_{M3}(Fe + Al) = \frac{P_{M3}}{[Fe_{M3} + Al_{M3}]} \times 100 \quad (14)$$

$$PSD_{M3}(Ca) = \frac{P_{M3}}{[Ca_{M3}]} \times 100 \quad (15)$$

The “higher PSD values point out that soil has a low capacity to hold additional P safely and is associated with increased P concentration in soil solution, surface water runoff and leaching” (De Bolle, 2013; Schoumans & Chardon, 2014; Sharpley & McDowell, 2016).

**Maximum P sorption capacity (P Sorption in soil test and retention):** To determine the maximum P sorption capacity of soil colloid for improved crop productivity and less P loss to surface and groundwater (environment). The batch sorption experiment were conducted where selected soil samples with known inherent P levels were incubated and allowed to equilibrate with a solution of varying P concentrations for 24 hours, and after 24 hours, the concentration of P remaining in soil solution and that adsorbed to soil colloid were determined as described by Van Der Zee and Van Riemsdijk (1986) and Schoumans and Chardon (2014).

In summary, “about 1 gram of air-dried soil (<2 mm) were weighted using a digital analytical balance and added to 50 ml centrifuge tubes, then 25 ml of phosphate (P) solution containing 0 mg/L, 0.1 mg/L, 0.2 mg/L, 0.5 mg/L, 1 mg/L, 2 mg/L, 5 mg/L, 7.5 mg/L and 10 mg/L as dihydrogen potassium phosphate ( $\text{KH}_2\text{PO}_4$ ) were added to each centrifuge tube. All soil samples were normalised using calcium chloride (0.01M  $\text{CaCl}_2$ ) as a background solution because in natural land most soil solution have 0.01M  $\text{CaCl}_2$ , which allow better plant nutrient availability; thus, the experiment is trying to simulate the sorption and desorption of P under normal and natural condition. In addition, 1 ml of 0.02% (w/v) sodium azide ( $\text{NaN}_3$ ) were added to the solution to suppress biological activity, which can potentially increase or reduce the P added. The mixture was loaded in the end to end mechanical shaker and shaken for 24 hours at room temperature (20°C). The soil suspensions were centrifuged at 1500 rpm for 10 minutes at a temperature of 20°C and allowed to settle for thirty minutes on a working bench. The solution were filtered through a 0.45 $\mu\text{m}$  Whatman membrane filter (Whatman #42) using a Buchner funnel and flask set-up connected to a vacuum pump to obtain clear filtrates. The concentration of P in the obtained filtrates (P remaining in solution) were determined colourimetrically by the method of Murphy and Riley (1962) based on a molybdenum blue (Mo)-based mixture in UV spectrophotometer (882 nm)” (Murphy & Riley, 1962).

The P adsorption (amount sorbed = Q), which shows the sum of P sorbed by the soil as the indication of the capacity of the soil to fix and release added P were determined experimentally using P sorbed in soil colloids (Q), and P concentration remained in soil solution (CP) after 24 hours of shaking. The concentration of P sorbed in soil colloids (Q) determined by taking the

difference of P added (AP) minus the P concentration determined in filtrates after 24 hours (CP) (Equation 16).

$$Q \text{ (mmol/kg)} = AP - CP \quad (16)$$

### 3.3.3. Objective 3: To assess soil quality in different paddy farming areas

**Defining the rice farming system:** Paddy farming areas were characterized by observatory assessment where elements of the farming system were identified; this included source waters, soil fertility management strategies used, irrigation water recycling, vegetation on paddy field borders where effluents end and designed arrangement of paddy fields bunds in the area.

**a) Soil Quality:** Soil quality in Usangu agro-ecosystem was determined based on the USDA and Verdoodt soil quality guidelines (Verdoodt, 2008). Different indicators were tested as a reflection of soil quality in the study area. The indicators or parameters studied included soil organic carbon (SOC), texture, soil pH, electrical conductivity, plant-available P and Nitrate-N, and soil moisture content (MC). The SOC, soil pH, P, and N were determined by the method described in sections 3.2 and 3.3.1. The soil electrical conductivity (EC) was determined by conductivity meter and cell in 1:5 soil: water suspension.

**b) Soil invertebrate (earthworms) diversity:** To determine the influence of farming activity and other anthropogenic activity happening in UA on soil invertebrates. Soil invertebrates (earthworms) surveys were conducted in selected paddy rice irrigation schemes. Due to limited resources and their importance, special attention were given to earthworm population and diversity as it plays a significant role in soil fertility, land productivity, environmental quality and sustainability. Furthermore, earthworm population and diversity worldwide is widely used as a bioindicator to assess environmental contamination.

The earthworm survey in UA conducted based on the protocol adapted from Mcinga *et al.* (2021) with slight modifications, where irritating oil were not used as suggested by the original source due to the fact that irritating oil was not able to force earthworms to come up to the soil surfaces as most earthworms were not in few centimetres from the soil surface due to less organic matter or crop residues. The survey was conducted mainly in 10 irrigation schemes, namely Mubuyuni, Uturo, Kapunga, Ukwavile, Ihahi, Chimala, Isenyela, Igalako, Mahongole and Mabadaga, which reflect the extent of intensified paddy rice farming in Usangu agro-ecosystem.

In each survey site, a 35 cm × 35 cm quadrat were randomly placed at each sampling point, and the mark were drawn outside the quadrat to demarcate the area selected (Kamota *et al.*, 2012). The soil were dug to a depth of 50 cm to cover the selected area in the quadrat; the dug soil were spread on the plastic mat to capture and handpick the obtained earthworms. The number and fresh weight of collected earthworms were recorded to the nearest 0.01 grams. After recording the fresh weight, earthworm were euthanised in 70% ethanol and stored for later classification using the Dichotomous key for earthworm identification (NRRI 2011). For statistical purposes, 5 replicate sampling points per site were conducted to calculate the mean and standard deviation values per site. The distance between one pit (or sampling point) and another pit per site was at least 100 meters.

The collected earthworms were dried at 60°C in the oven for a minimum of 24 hours to constant weight to measure their dry biomass. After dry weighing, the dried earthworms were placed in a muffle furnace at 500°C for approximately 5 hours to burn off all combustible parts to determine “ash-free-dry-biomass”. In this study, the ash-free dry biomass were used as the final earthworm biomass. The ash-free dry biomass of the earthworms calculated by subtracting ash contents of the earthworm from oven-dry weight.

The earthworm Shannon diversity index (H) and species evenness (E) were determined by the method proposed by Mcinga *et al.* (2021) in equations 17 and 18.

$$H = \sum_{i=1}^n -(P_i \times \ln P_i) \quad (17)$$

Where “H = the diversity index; Pi = fraction of the entire sample made up of species i; n = numbers of species encountered;  $\sum$  = sum from species 1 to species n” (Mcinga *et al.*, 2021).

$$E = \frac{H}{H_{Max}} \quad (18)$$

Where E = species evenness;  $H_{Max}$  = maximum diversity possible and  $H = \ln(N)$ .

#### **3.3.4. Objective 4: To evaluate the PTE accumulation and distribution in soils and plants in Usangu agro-ecosystem**

From all “soils, waters and plant samples, PTEs accumulation and distribution were estimated to understand its concentrations levels, distribution, and pollution indexes in UA. PTEs such as Cr, Al, Mn, Fe, Co, Ni, Cu, Pb, As, Se, Cd and other PTEs as shown in results tables, from soils, plants, sediments, and water samples were determined. The total and bioavailable

concentrations were determined by *aqua regia* acid digestion (total concentration) and M3 extraction solution (bioavailable concentration), respectively. PTEs measurements were conducted in the ISO-accredited analytical chemistry laboratories of School of Geography, Earth and Environmental Science (SOGEEES) at University of Plymouth, United Kingdom. The total PTEs (*aqua regia* extracts) and bioavailable PTEs (Mehlich 3 extracts) from collected air-dried soil samples (<2 mm) determined as follows:” (Mng’ong’o *et al.*, 2021).

**Total PTEs concentrations.** Soil and sediments samples were digested in an acid mixture of concentrated hydrochloric acid (HCl) and nitric acid (HNO<sub>3</sub>) from Sigma-Aldrich Chemie GmbH in the method commonly called *Aqua regia* (AQ) in a ratio of 3:1 (v/v) in a hot plate for at least three hours (UoP, 2015). In summary, “approximately 0.2 grams of air-dried fine soil or sediment samples were weighed and placed in a 25 ml beaker. Then, 1 ml of high purity HNO<sub>3</sub> were added and allowed to cold digest for 1 hour. After 1 hour, 3 ml of high purity HCl and additional 1 ml of HNO<sub>3</sub> were added and allowed to hot digest (90-180°C) for at least 3 hours until brown fumes stopped evolving from the mixture. When solution observed to boil dry, additional HCl and HNO<sub>3</sub> were added in a 3:1 ratio. All soil digestion were conducted in a fume hood because some of the evolving gases are poisonous. After three hours of acid digestion, the extract mixture were cooled and filtered into a 25 ml volumetric flask using an 0.42 µm acid-resistant membrane filter (Whatman #42). The collected filtrates were made to the mark by using 2% HNO<sub>3</sub> (v/v) solution and were stored at 4°C until analysis. During every acid digestion session, three blanks were included comprising all digestion reagents at the same amount as sample digestion, but no soil samples were added; this was made purposely to monitor any contamination which might be happening due to reagents and glassware” (Mng’ong’o *et al.*, 2021). The roots samples collected were first clean by tape water at the site of sample collection to remove all soil particles and afterwards were washed with distilled water to remove tape water and remaining soil particles as a way to avoid PTEs which might be associated with soil particles rather than those accumulated in root tissues.

**Bioavailable PTEs concentrations.** “The bioavailable PTEs were extracted by M3 extraction solution (M3) (Guo, 2009a; Mehlich, 1984). Where, 2 grams of air-dried soil samples were weighed and placed into 50 ml centrifuge tubes, followed by the addition of 20 ml of M3 extraction solution, tied, and shaken in an end to end mechanical shaker at 180 rpm for five minutes at room temperature (20°C). Then the mixture was centrifuged at 1200 rpm for 5 minutes and filtered into a 10 ml volumetric flask through a 0.42 µm acid-resistant Whatman

No.42 filter. All sample extracts were measured in triplicate. The PTEs concentrations in soil extracts (*aqua regia* and Mehlich 3 extracts) were determined by ICP-MS (Thermo Scientific iCAP TQ MS Ermentrude) and ICP-OES (Thermo Scientific iCAP 7400 ICP-OES Pickles) at SOGEES labs-UK” (Mng’ong’o *et al.*, 2021).

**Quality control and assurance:** To ensure the reliability of the generated data, “reagent blanks, certified reference soil material SCP (S150123029) and SS-2 EnvironMAT (S150827031) from SCP Science-Qmx laboratories, Thaxted-UK were used to monitor determination quality of soil samples in M3 method and *Aqua regia*, respectively. Furthermore, glasswares were acid washed with dilute 10% HNO<sub>3</sub> (v/v) and 10% HCl (v/v), followed by four times washing with distilled water and finally rinsed thrice with Milli-Q water to avoid any trace of contamination. Moreover, all reagents and calibration standards were prepared by Milli-Q water. The recovery of samples spiked with standards ranged 83% to 105% for M3 and 74.78% to 98.10% for AQ (Appendix 4). Therefore, PTEs values obtained in this study were in close agreement with the certified values” (Mng’ong’o *et al.*, 2021).

**Soil pollution evaluation:** To assess the contamination of agricultural soils with PTEs, maximum permissible limits were extracted from “Tanzania (TZ) environmental management (soil quality standards) regulations guideline of 2007 (URT, 2007), and compared with those from international regulatory authorities such as Canada (CCME, 2007) and United States Environmental Protection Agency (USEPA) values (USEPA, 1992)”. The obtained values were based on total PTEs concentration, and the obtained values used to assess contamination and pollution status of agro-ecosystem. Any values obtained that were observed to be above established maximum permissible limit were considered to indicate pollution or contamination risks (Table 12).

To estimate the PTEs contamination or pollution hierarchy in agro-ecosystem, “the ratio of total PTEs with maximum permissible limits (AQ:TZ, and AQ:USEPA) were computed to estimate adverse effect index (AEI). Where a higher ratio of greater than 1 indicated high contamination or pollution risk, thus, control measures have to be installed to avoid further PTEs accumulation and associated impacts. In addition, to estimate the fraction of total PTEs (AQ) available for plant uptake from determined bioavailable PTEs (M3), a ratio of M3:AQ computed as an estimate for PTEs bioavailability, where a higher ratio represents higher PTEs accessibility and potential environmental risks to soil invertebrates, animals and human. From the generated data of PTEs in Usangu agro-ecosystem, the following were determined: (a)

PTEs spatial distribution in agricultural soils across agro-ecosystem, (b) comparison of total PTEs versus bioavailable soil PTEs concentrations and compared with published environmental quality guidelines, and (c) PTEs among land use” (Mng’ong’o *et al.*, 2021).

**Table 12: Eestablished allowable levels (maximum permissible limits) of PTEs in agricultural soils and plants from Canada, USEPA, and Tanzania**

PTEs	Concentration (mg/kg dry wt)			
	Soils			Plants
	TZ Maximum Permissible Limit	Canadian Maximum Permissible Limit	USEPA Maximum Permissible Limit	FAO/WHO maximum permissible limit
Fe	5000	-	-	425
As	1	12	0.2	-
Se	20	1	20	-
Cd	1	1.4	0.1	0.5
Cr	100	64	1	1
Ni	100	50	50	0.5
Cu	200	63	2	2
Hg	2	6.6	0.005	-
Mn	1800	-	5	100
Pb	200	70	0.1	2
Zn	150	200	5	60

Source (CCME, 2007; Choi, 2011; Emurotu & Onianwa, 2017; URT, 2007; USEPA, 1992)

**Soil and water contamination pollution indexes:** To determine nutrients causing eutrophication, i.e., nitrogen (TN) and phosphorus (TP) and PTEs contaminations in the study area, the risk of PTEs accumulation in agro-ecosystem were estimated by various indexes as described below.

**Organic index:** This involves ecological risk assessment of fertility in water samples and sediments; this were determined by Equation 19.

$$\text{Organic index} = \text{Organic carbon (\%)} \times \text{organic nitorgen (\%)} \quad (19)$$

Where “organic nitrogen (%) is is a computed by multiplying total N (TN) by 0.95 (Organic nitrogen(%) = TN(%)x0.95) since TN is the inclusion of organic N (OC-N) and ammonium-N, and OC-N occupy the absolute majority of TN. The interpretation of organic index is as follows: Oligotrophic (< 0.03), Mesotrophic (0.03–0.05), and Eutrophic (>0.05)” (Li *et al.*, 2019).

**Potential ecological risk coefficient ( $E_r^i$ ):** The  $E_r^i$  of each PTEs were calculated based on Equation 20.

$$E_r^i = T_r^i \frac{C^i}{C_n^i} \quad (20)$$

Where " $E_r^i$  is the potential ecological risk coefficient of the  $i^{\text{th}}$  PTEs;  $T_r^i$  is the PTEs toxicity coefficient of the given metals,  $C^i$  and  $C_n^i$  are the PTEs concentration in the sample (soil) and background, respectively" (Li *et al.*, 2019).

**Comprehensive risk index (RI):** This is calculated for all metals as their effect usually occurs in combinations rather than individual element; the RI were determined by Equation 21. The RI show the toxicity of PTEs to soil organisms and other organisms that can come in contact with soils direct or indirectly such as through water and sediments; the RI shows whether PTEs toxicity is low, moderate or high, as shown in Table 13.

$$RI = \sum_{i=1}^m E_r^i \quad (21)$$

Based on the RI and  $E_r^i$  the degree of PTEs pollution or contamination in soils and sediments is classified into five classes (low to very high), as shown in Table 13.

**Table 13: The five ecological risk level classess of PTEs**

Risk Level	Low	Moderate	Considerable	High	Very high
$E_r^i$	<40	40-80	80-160	160-320	>320
RI	<95	95-190	190-380	-	>380

(Source; Hakanson, 1980).

**Total PTEs concentrations:** The total concentrations of PTEs in agricultural soils and sediments were analyzed and compared to maximum monitoring authorities values established as the maximum PTEs concentration limits in agricultural soils, natural habitats, and water (URT, 2007). The total concentrations of metals were determined and compared with maximum permissible limits developed by respective regulatory authorities.

**Contamination Factor (CF) and Pollution Load Index (PLI);** The "pollution load index (PLI) is the square root of the multiplication of the contamination factor (CF) of PTEs (Equation 22): where CF (metal) is the ratio between the content of each PTEs and the background value in soil, sediment or water samples of the study area" (Li *et al.*, 2019) as shown in Equation 23. The CF and PLI were determined and used to evaluate PTEs contamination. The interpretation of CF and PLI values were described in Table 14.

$$CF (Metals) = \frac{C(metal)}{C(background)} \quad (22)$$

$$PLI = (CF1 \times CF2 \times CF3 \times \dots \times CFn)^{1/n} \quad (23)$$

**Table 14: Summary description of the interpretation of CF and PLI indexes**

	CF class	Low pollution	Moderate pollution	High pollution	Very high pollution
1	CF Value	<1	1-3	3-6	>6
2	PLI class	Perfect site/no pollution	Base line pollution	Deterioration of site quality	
	PLI value	<1	1	>1	

**Geoaccumulation Index ( $I_{geo}$ );** To assess the PTEs contamination degree in agro-ecosystem were conducted by the geo-accumulation index ( $I_{geo}$ ). Where  $I_{geo}$  calculated as described in Equation 24.

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right) \quad (24)$$

Where “ $C_n$  is the  $n$ PTEs in the sample,  $B_n$  is the background  $n$ PTEs concentration, and 1.5 is a lithological changes factor. The  $I_{geo}$  class are described into seven categories” (Uddin *et al.*, 2021), as shown in Table 15.

**Table 15: The description and interpretation of geoaccumulation ( $I_{geo}$ ) classes in agricultural soils**

$I_{geo}$ class	Uncontaminated (UC)	Uncontaminated to moderately contaminated (UMC)	Moderately contaminated (MC)	Moderately to heavily contaminated (MHC)	Heavily contaminated (HC)	Heavily to extremely contaminated (HEC)	Extremely contaminated (EC)
$I_{geo}$ value	< 0	$0 \leq I_{geo} < 1$	$1 \leq I_{geo} < 2$ ,	$2 \leq I_{geo} < 3$	$3 \leq I_{geo} < 4$	$4 \leq I_{geo} < 5$	$\geq 5$

**Enrichment Factor (EF);** The EF of potentially toxic elements is used to evaluate anthropogenic contamination. Where iron (Fe) was selected as a normalizing element for identifying PTEs anomalous contributions (Vemic *et al.*, 2014), the EF values were estimated based on Equation 25.

$$EF = \frac{C/Fe(sample)}{C/Fe(background)} \quad (25)$$

Where “ $C/Fe$  (sample) is the ratio of PTEs to Fe in soil sample, and  $C/Fe$  (background) is the ratio of PTEs to Fe in the background. The EF are classified into five classes as follow:  $EF < 2$  = minimal enrichment,  $EF 2-5$  = moderate enrichment,  $EF 5-20$  = significant enrichment,  $EF 20-40$  very high enrichment, and  $EF > 40$  = extremely high enrichment” (Nkinda *et al.*, 2020).

**Potential toxic element (PTEs) determination in plant samples:** To characterize the PTEs translocation and bioconcentration from agricultural soils to plants were determined by determining the concentration of PTEs in plants and soil samples where particular plant samples were growing as follows;

**The PTEs concentration in soil and plant:** All collected “soil and plant samples were grounded to pass 0.63 mm sieve and then digested in an acid mixture of concentrated HCl and HNO<sub>3</sub> (aqua regia (AQ)) at 3:1 ratio in a hot plate (90-108°C) for at least three hours, where 0.2g soil or plant samples were weighed into 25 ml heatable beaker. Then 1 ml of HNO<sub>3</sub> were added and the mixture was covered with a watch glass and left at room temperature (20-25°C) for 1 hour. Then, 3 ml of concentrated HCl and additional 1 ml of HNO<sub>3</sub> added and the mixture were heated on a hot plate for digestion (90-108°C) for at least 3 hours until production of brown fumes stopped, this conducted to ensure complete digestion. After digestion, the sample were cooled and filtered into 25 ml volumetric flask using an acid-resistant filter (Whatman filter No.42), then extract were made to the mark with 2% HNO<sub>3</sub>, and all extracts were stored at 4°C until analysis. A blank was also prepared for each digestion with the same amount of acids without a sample. All digestion processes and associated activities were conducted in the fume hood due to the production of poisonous fumes from *aqua regia* mixture. All PTEs extraction from studied samples were conducted in triplicate, the concentration of PTEs in digestion extracts were analyzed by Atomic absorption spectrometry (AAS) as instructed by manufacturers. In total, nine PTEs (Co, Mn, Cd, Cu, Cr, Fe, Pb, Zn, and Ni) were measured to estimate the association of PTEs in soil and paddy rice plants samples in each section. Furthermore, the translocation (TF) and bioconcentration factor (BCF) were determined. The concentration of PTEs determined from soil and plant samples were compared with the established maximum allowable limits as shown in Table 12” (Mng’ong’o *et al.*, 2021).

**Bioconcentration factors (BCF)** were estimated by dividing the PTEs concentration in plant parts versus those in soil samples from the respective location (Equation 26) (Lugwisha, 2016).

$$\text{Bioconcentration Factor (BCF)} = \frac{[M \text{ Plant}]}{[M \text{ Soil}]} \quad (26)$$

Where “[M Plant] is the PTEs concentration in plant sample extracts and [M Soil] is the concentration of PTEs in soil sample extracts from the study area” (Lugwisha, 2016).

The “BCF of above 1 indicates higher uptake of PTEs in plants than in soil, while BCF of less than 1 show that there is more PTEs concentration in soil than those taken up by plants” (Lugwisha, 2016).

**Translocation factors (TF)** were determined to estimate the translocation of PTEs from roots (below-ground biomass) to shoots (above-ground biomass) in paddy rice plant samples (Equation 27)

$$\text{Translocation factor (TF)} = \frac{[M \text{ Shoot}]}{[M \text{ Roots}]} \quad (27)$$

Where “[M Shoot] and [M Roots] is PTEs concentration in shoot and roots extracts, respectively. The TF of above 1 indicates higher PTEs in above-ground biomass (shoots) than below-ground biomass (roots). The TF of less than 1 indicates more PTEs accumulate in roots than in shoots, whilst the TF=1 indicates the plant has accumulated an equal concentration of PTEs in shoots and roots” (Lugwisha, 2016).

### **3.3.5. Objective 5: To assess surface water quality in paddy farming areas in UA**

To accomplish this study objective, 42 water samples from ten paddy irrigation schemes in Usangu basin (Fig. 10) were sampled from November to December 2019 and April to June 2021. Water samples were taken in rivers, channels and paddy fields comprising 4 distinct parts: before water enters paddy fields (**intakes**), water in irrigation channels (**channels**), water in paddy fields and its distributaries (**infields**), and water after leaving paddy fields (**drainages**) (Fig. 10). The drainages were purposely collected to assess the influence of farming activity on water quality in the nearby aquatic ecosystem but also this helps to demonstrate how nutrient loss could potentially be a cause of reduced land productivity and water contamination.

About 500 ml of water samples were sampled and stored in acid-washed plastic bottles at 4°C until analysis. Prior to sampling, the sample bottles were washed by the water samples from respective sampling site three times where water was added to the bottle and poured down, then added for the second time and poured down again, and a third time, then water sample were collected through a plastic sieved funnel (<1 mm) to sample bottles to avoid larger organic materials and solid debris.

**Sample extraction and quality assurance:** From collected water samples, different chemical water quality parameters were determined using the analytical chemistry protocols as follows;

**Determination of Ca, Mg, K, Cu, Fe, and Zn;** These elements were determined by atomic absorption spectrophotometry, where 5 ml of caesium-lanthanum solution were added to a clean, dry 50 ml volumetric flask, and 45 ml of water sample were added. The standard and water samples were aspirated to flame absorption under the manufacturer's stipulated conditions (Motsara & Roy, 2008). The obtained absorbance reading values were used to calculate elemental concentrations based on the calibration curves obtained by plotting standard solutions concentrations versus corresponding absorbance readings. The Ca, Mg, K, Cu, Fe, and Zn concentrations in water samples were estimated by linear regression equation obtained from constructed standard curves based on standard solutions of respective elements.

**Determination of  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$ ;** The concentration of carbonates ( $\text{HCO}_3^-$ ) and bicarbonates ( $\text{CO}_3^{2-}$ ) as a measure of alkalinity in water samples were determined by titration method (Motsara & Roy, 2008). Where 100 ml water sample were added in 150 ml volumetric flask, 2 drops of phenolphthalein indicator were added. The mixture was titrated with 0.1M sulphuric acid until the colour mixture turned from purple to colourless. The volume of  $\text{H}_2\text{SO}_4$  used were noted and used to calculate the amount of  $\text{HCO}_3^-$  in water samples. Furthermore, two (2) drops of the mixed indicator were added, and the mixture turned blue, and then titration were continued with  $\text{H}_2\text{SO}_4$  until the colour changed from blue to red. The additional volume of  $\text{H}_2\text{SO}_4$  used were used to estimate  $\text{CO}_3^{2-}$  concentration and the total alkalinity of the water.

**Determination of Total P;** Total P in water samples were determined as described by Pierzynski (2000), where 50 ml of water samples were added in a volumetric flask, and 0.05 ml of phenolphthalein (POP) indicator were added and mixed well, 1 ml of  $\text{H}_2\text{SO}_4$  solution and 0.4 g of solid  $(\text{NH}_4)_2\text{S}_2\text{O}_8$  were added and mixed well. Then water samples were heated for 30 minutes on a hot plate until water samples were reduced to 10 ml, cooled and 0.05 ml of POP indicator was added before diluting the sample to 30 ml with distilled water. The total P concentration in digested water samples was determined spectrophotometrically (882 nm) by the method of Murphy and Riley (Murphy & Riley, 1962).

**Determination of chloride in water samples;** Chloride in water samples were determined by titration by Mohr's Method (Doughty, 1924; Korkmaz, 2011), where 25 ml of water samples were titrated with silver nitrate solution using potassium chromate as an indicator. The determination of total nitrogen (Total N), ammonium nitrogen ( $\text{NH}_4\text{-N}$ ), and nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ) in water samples were determined by Kjeldahl Methods (Motsara & Roy, 2008).

**Quality assurance:** To ensure data reliability, reagent blanks and standard reference solutions were utilized to monitor the determination quality. Throughout the study, analytical-grade chemicals or reagents were employed without further purification. To avoid contamination of the corresponding elements, all calibration standards and working solutions were made with twice distilled water. In addition, to avoid contamination, all glassware were washed with dilute 10% HNO<sub>3</sub> and 10% HCl, followed by three times rinse with double-distilled water.

### 3.4. Data analysis

The collected data were analyzed by different statistical software such as IBM SPSS 24 (IBM, 2013), GenStat, Jamovi 2.2.5, Minitab 14, origin Pro and Sigma plot. Where different statistical methods were applied to analyze distribution and correlation among different studied parameters. The collected data were tested for normality (by Levene's test and Bartlett's test), equality of variance (tested by Shapiro-Wilk, Kolmogorov-Smirnov and Anderson-Darling test) and linearity of the data were tested by Cook's distance, and Collinearity test (VIF) where the *P* values were above 0.05 showing data were normally distributed, had equality of variance and linear trend as the requirement for most inferential statistics (ANOVA, regression, etc.) conducted in this study and provide varied generalized conclusion and recommendations.

Where “All collected PTEs data were statistically analyzed by the Jamovi 2.2.5, JASP 0.6.12, and IBM SPSS Statistics 24 programs (IBM: Chicago, IL, USA). A descriptive statistical analysis was performed to define the physical and chemical soil properties of the study areas. The computed mean values were compared with the regulatory values to evaluate the magnitude of nutrients or contaminants in the agro-ecosystem or environment. The statistical difference among irrigation schemes, land use, and sampling points within and between irrigation schemes were determined by one-way ANOVA and Tukey post hoc tests ( $P < 0.05$ ). To understand the relationship of the PTEs in soil, plants, and water, Pearson correlation analyses were performed. The study site, sampling points, and concentration maps were generated using the QGIS 3.10.7 software and were used to map study site, concentration maps, and PSC and PSD spatial distribution in the study area; for detail (Table 16). All plots and graphs were generated in origin Pro 9.0 and Minitab 14” (Mng'ong'o *et al.*, 2021).

**Table 16: Summary of parameters measured, analyzed and the statistical package used**

<b>Objective</b>	<b>Statistical analysis conducted</b>	<b>Statistical package used</b>
1	ANOVA for Mean values for total P, N, K, Ca, Mg, pH, OC, PTEs, EC.	IBM SPSS, Jamovi, and Genstat
2 and 5	ANOVA for mean values of PSC, PSD, $P_{M3}$ , $Al_{M3}$ , $Fe_{M3}$ , $Ca_{M3}$ , sorbed and desorbed P, Correlation analysis of how PSC, PSD vary with $Al_{M3}$ , $Fe_{M3}$ , $Ca_{M3}$ , eutrophication events and elevation gradient	IBM SPSS, Genstat, Sigma Plot, Minitab 14, and QGIS
3	ANOVA of mean values of soil pH, C, N, P, EC, earthworm counts, diversity. Correlation of parameters above with land use and elevation gradient.	IBM SPSS and Genstat
4	ANOVA of mean values of PTEs (Cr, Cd, Pb, Cu, Hg and As) from different sites. Correlation of parameters above with land use locations and elevation gradient.	IBM SPSS, Jamovi, and Genstat.

## CHAPTER FOUR

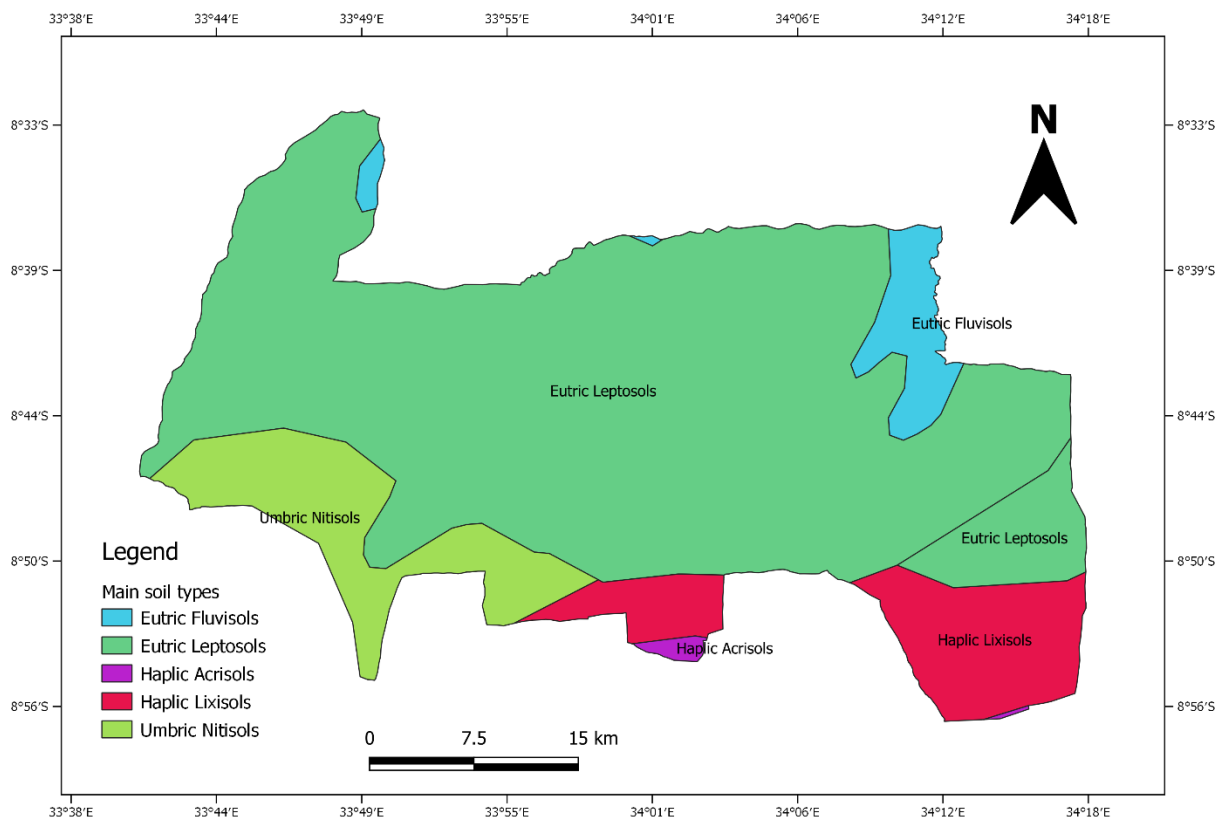
### RESULTS AND DISCUSSION

#### 4.1. Results

##### 4.1.1. General soil properties and soil fertility in Usangu agro-ecosystem

Soil fertility parameters assessed were Al, P, OC, Mg, pH, K, N, Ca, S and micronutrients such as Zn, Fe, Mn, Cr, and Cu based on various established international standard analytical methods. The concentration of studied plant nutrients and fertility status across land use and irrigation schemes presented in Table 17. The major soil types which were predominant in the study area were Haplic Acrisols, Eutric Fluvisols, Umbric Nitisols, Eutric Leptosols, and Haplic Lixisols (Fig. 11) which can highly influence the fertility status and management in a particular irrigation schemes (FAO, 2014; Wickama & Mowo, 2001). In summary the description of major soil types found in the area were:

**Eutric Fluvisols**, are soils commonly found in level or plain topography (flood plain and great river basins) which are periodically flooded by surface or ground waters. Eutric fluvisols are product of regular deposition of materials from lakes, rivers or surface runoffs at regular intervals and are usually soils with evidence of stratified profile that shows irregular layers of humus and minerals as a result of depositional history in which organic carbon content decreases with depth (FAO, 2014; Wickama & Mowo, 2001). Furthermore, eutric fluvisols have base saturation (by 1 M ammonium acetate (NH<sub>4</sub>OAc)) of 50% or more between 20 and 100 cm depth from soil surface or between 20 cm and continuous rock. This soil type is commonly used for dryland crops or rice cropping and grazing in the dry season (FAO, 2006).



**Figure 11: The major soil types commonly observed in Usangu agro-ecosystem**

**Haplic Acrisols:** These are soils found in undulating humid tropical topography, which have extensive leaching and low concentration of plant nutrients, but also have excess Al and associated with higher risk of soil erosion making agriculture problematic, especially if located on the hilly farms, however, the soil is better suited for acid-tolerant crops (FAO, 2006). Furthermore, haplic acrisols have a subsurface layer dominated by kaolinitic clays where less than 50% of the ions (Ca, Mg, Na, or K) are available for plant uptakes due to extensive leaching in the surface horizon (upper most layer).

**Umbric Nitisols:** This is a deep, red, well-drained soil with a clay content of more than 30% and a blocky structure (FAO, 2006). Umbric Nitisols are formed from fine-textured weathered material from intermediate to basic parent rock, and kaolinite, halloysite and iron oxides dominate their clay mineralogy. The soil has base saturation (by 1 M  $\text{NH}_4\text{OAc}$ ) of less than 50% throughout the horizon depth up to one meter. The Umbric Nitisols are usually dominated by heavy forest and savannah, but also the soil has frequently low phosphorus availability and low base status limitations; but once ameliorated, these deep, stable soils have high agricultural potential and are often planted as the scenario observed in Usangu agro-ecosystem.

**Haplic Lixisols:** The soil which usually found in tropical landscape associated with dry season, they are characterized by the presence of a subsurface layer rich in kaolinitic clays and extensive leached surface layer where 50% of readily displaceable ions are Ca, Mg, Na, or K. The soil have soil mineralogy which has low soil nutrients and is associated with higher soil erodibility, thus, agriculture in these soils is achieved by minimum tillage, frequent fertilizer applications, and intensive soil erosion management (FAO, 2014; Wickama & Mowo, 2001). The soil is suitable for perennial; or tuber crops such as potatoes, as evidenced in Usangu agro-ecosystem.

**Eutric Leptosols:** This type of soil is characterized by very shallow soil profile depth (indicating little influence of soil-forming processes), and mostly contains larger proportions of gravels. Chemically eutric leptosols have base saturation (by 1 M  $\text{NH}_4\text{OAc}$ ) of 50% or more in the major part between 20 and 100 cm from the soil surface or between 20 cm and continuous rock or a cemented or indurated layer (FAO, 2006). They typically remain under natural vegetation since they are susceptible to soil erosion, desiccation, or waterlogging, depending on climate and topography. Due to continuous erosion by wind or water erosion and shallow horizon depth to hard bedrock, Leptosols show little or none of the horizonation. In Usangu agro-ecosystem in the study area, this type of soil was the most dominant soil type, and they have low soil fertility, necessitating higher fertilizer use to achieve desired productivity.

#### **(i) Soil pH and electric conductivity (EC)**

Soil pH affects soil biogeochemistry and is regarded as a chief soil variable that regulates plant development and biomass yield by controlling biological, chemical, and physical aspects of the soil (Neina, 2019). The soil pH in studied soils from Usangu agro-ecosystem was almost in all soil samples ranged 6.4 to 7.6 (Table 17), where among 198 samples, 19 had soil pH below 6.5, which has an influence on the solubility and availability of plant nutrients such as N, Mg, P, K, Ca, S, and other bases. The pH values of the other soil samples ranged from 6.5 to 7.6, which were within the optimum and tolerable pH limits for crop growth (6.5 to 8.5). Furthermore, the studied soils had higher extractable Al (93.21 to 792.97 mg/kg), indicating availability of extractable acidity. The soil electric conductivity (EC) in soil paste in UA were observed to range from 69.70 to 196  $\mu\text{S}/\text{cm}$  (Table 17). The determined EC (69.7 to 196  $\mu\text{S}/\text{cm}$ ) which ranged medium to high. Higher EC (in  $\mu\text{S}/\text{cm}$ ) values in UA were observed in Ilaji (196), Igalako (128.03) and Uturo (100.9).

**Table 17: Summarized average general chemical soil properties for studied samples from Usangu agro-ecosystem**

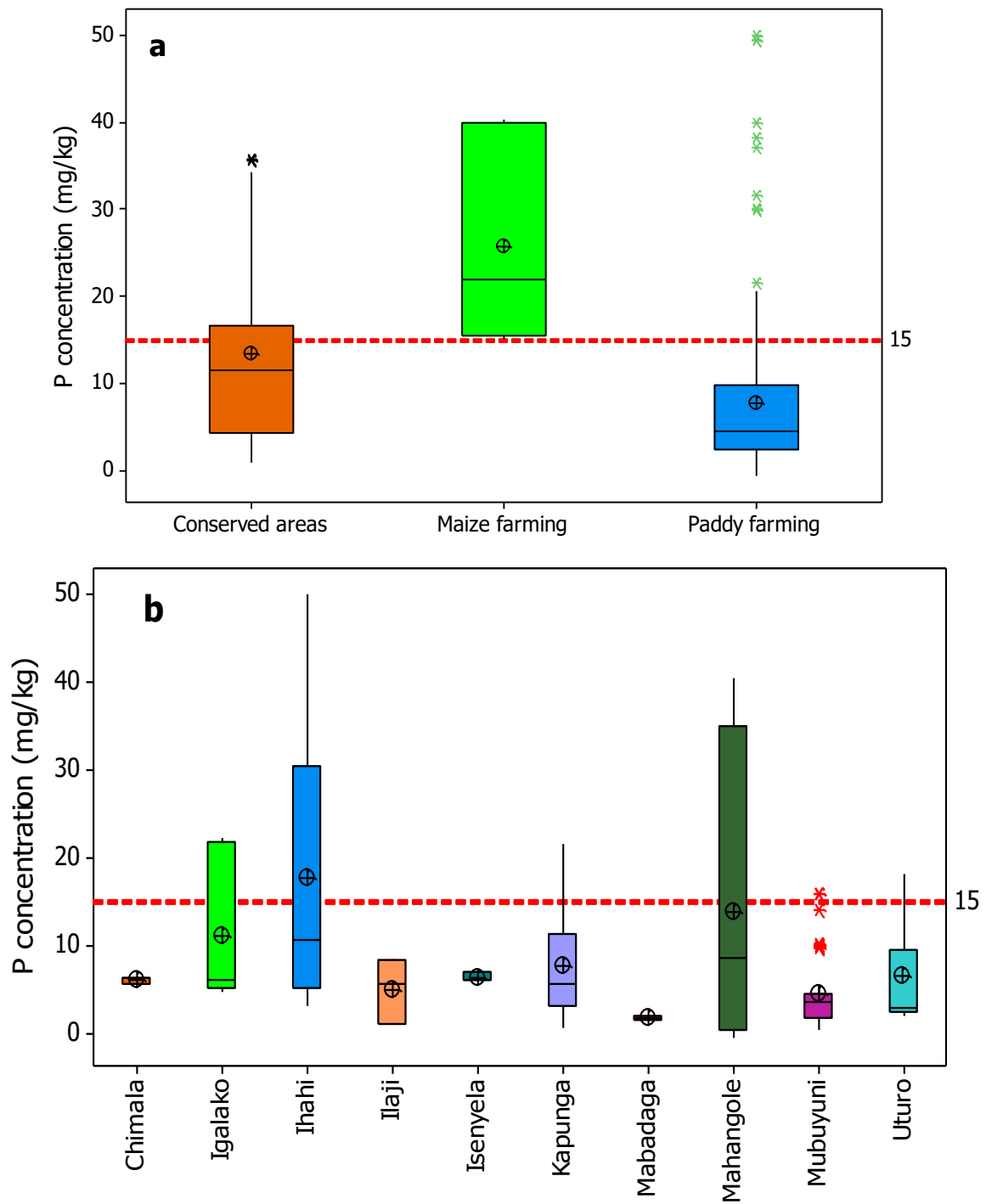
<b>Irrigation schemes</b>	<b>EC (<math>\mu\text{S/cm}</math>)</b>	<b>pH</b>	<b>N (%)</b>	<b>OC (%)</b>
Ihahi	69.70	6.92	0.07	0.80
Igalako	128.00	6.88	0.06	0.68
Mabadaga	78.50	7.39	0.11	1.33
Mahangole	91.70	6.41	0.11	1.37
Ilaji	196.00	7.22	0.17	2.37
Chimala	88.00	7.11	0.05	0.60
Kapunga	89.00	7.35	0.04	0.45
Mubuyuni	83.00	7.64	0.03	0.37
Isenyela	71.40	6.60	0.06	0.75
Uturo	100.90	6.65	0.16	1.99
<b>Overall mean</b>	<b>99.62</b>	<b>7.02</b>	<b>0.09</b>	<b>1.07</b>
<b>SD</b>	<b>37.74</b>	<b>0.39</b>	<b>0.05</b>	<b>0.68</b>
Minimum	69.70	6.41	0.03	0.37
Maximum	196.00	7.64	0.17	2.37

**(ii) Plant available phosphorus (P)**

The plant-available P ( $P_{M3}$ ) concentration was determined by M3 method (Mehlich, 1984), a standard and universal method for soil P test in numerous laboratories worldwide, but also M3 have a strong correlation ( $P < 0.001$ ,  $R^2 = 0.987$ ) with other popular and well-known soil P test, i.e., Bray 1 P and Olsen (Kleinman & Sharpley, 2002; Sims *et al.*, 2002). The general trend for available  $P_{M3}$  was observed to range from 0.52 to 48.87 mg/kg, where some were above recommended levels of P for upland soils (15.0 mg/kg) (Wasonga *et al.*, 2010). It was found that the majority of studied sites had a mean  $P_{M3}$  concentration less than 15.0 mg/kg. The analysis of  $P_{M3}$  concentration among land use varied significantly ( $P < 0.05$ ) (Table 18 and Fig. 12a), where  $P_{M3}$  concentration were; paddy farming areas (0.52 to 49.87 mg/kg) with mean values of 7.7 mg/kg, maize farming areas (15.2 to 40.32 mg/kg) with a mean value of 25.73 mg/kg, and conservation areas (0.99 to 35.79 mg/kg) and mean value of 13.49 mg/kg. High  $P_{M3}$  concentrations (above 15 mg/kg) were observed in maize farming areas. The P concentration spatial distribution among land use shows that paddy farming areas had lower  $P_{M3}$  content than the other two land use, even though farmers in paddy farming areas have a high use of N and P-fertilizer. Although conservation areas are protected from human activities and left for natural vegetation to grow, the  $P_{M3}$  concentration determined in soils from conservation areas ranged low (0.99) to high (35.79 mg/kg), which was adequate to permit natural vegetation growth and regeneration.

**Table 18: Soil nutrient concentration (in mg/kg dry wt.) among three land-use (conservation areas, paddy and maize farming areas) in UA**

	Land Use	Al	Ca	Cu	Fe	K	Mg	Mn	P	S	Zn
Mean	Conserved areas	214.91	919.65	1.78	174.83	500.09	300.97	152.94	13.49	16.72	3.53
	Maize farming	193.60	1362.55	0.70	107.03	647.14	286.87	220.46	25.73	23.09	3.64
	Paddy farming	294.10	806.89	2.03	214.81	399.75	238.59	137.03	7.70	22.44	2.14
95% CI mean	Conserved areas	186.12	658.93	1.24	140.08	354.71	238.43	104.32	8.25	13.09	2.60
	Maize farming	150.33	1342.27	0.59	97.06	631.27	271.55	196.84	18.49	16.99	3.44
	Paddy farming	268.69	734.29	1.81	201.94	358.16	214.92	124.88	6.31	19.66	1.98
95% CI upper bound	Conserved areas	243.70	1180.37	2.31	209.58	645.47	363.50	201.56	18.73	20.35	4.46
	Maize farming	236.86	1382.84	0.82	117.00	663.02	302.19	244.08	32.97	29.19	3.84
	Paddy farming	319.50	879.50	2.26	227.68	441.34	262.25	149.17	9.09	25.22	2.30
Standard deviation	Conserved areas	62.32	564.37	1.17	75.23	314.70	135.37	105.25	11.34	7.86	2.01
	Maize farming	66.23	31.06	0.17	15.26	24.30	23.45	36.15	11.09	9.34	0.30
	Paddy farming	166.50	475.83	1.49	84.34	272.57	155.08	79.58	9.11	18.22	1.07



**Figure 12: The boxplot show soil P distribution among 3 land use (a) and schemes (b) in Usangu agro-ecosystem; the dotted line represents the optimum P concentration recommended in upland soils, the cycle with a + sign represents mean values**

The spatial soil P<sub>M3</sub> concentration distribution in different schemes studied in UA varied significantly ( $P<0.05$ ) different, where schemes with higher P<sub>M3</sub> (in mg/kg, maximum values) were Ihahi (49.85), Mahongole (40.32), Uturo (24.5), Kapunga (21.5), and Igalako (22.1) (Fig. 12b and Table 19). These schemes are located in the lowland section of UA, getting runoff from the higher parts of the basin, and are among schemes practicing most intensive farming (Ngailo *et al.*, 2016). Low P concentrations were found in the remaining schemes, such as Ilaji, Chimala, Mubuyuni, Isenyela, and Mabadaga (Fig. 12b and Table 19).

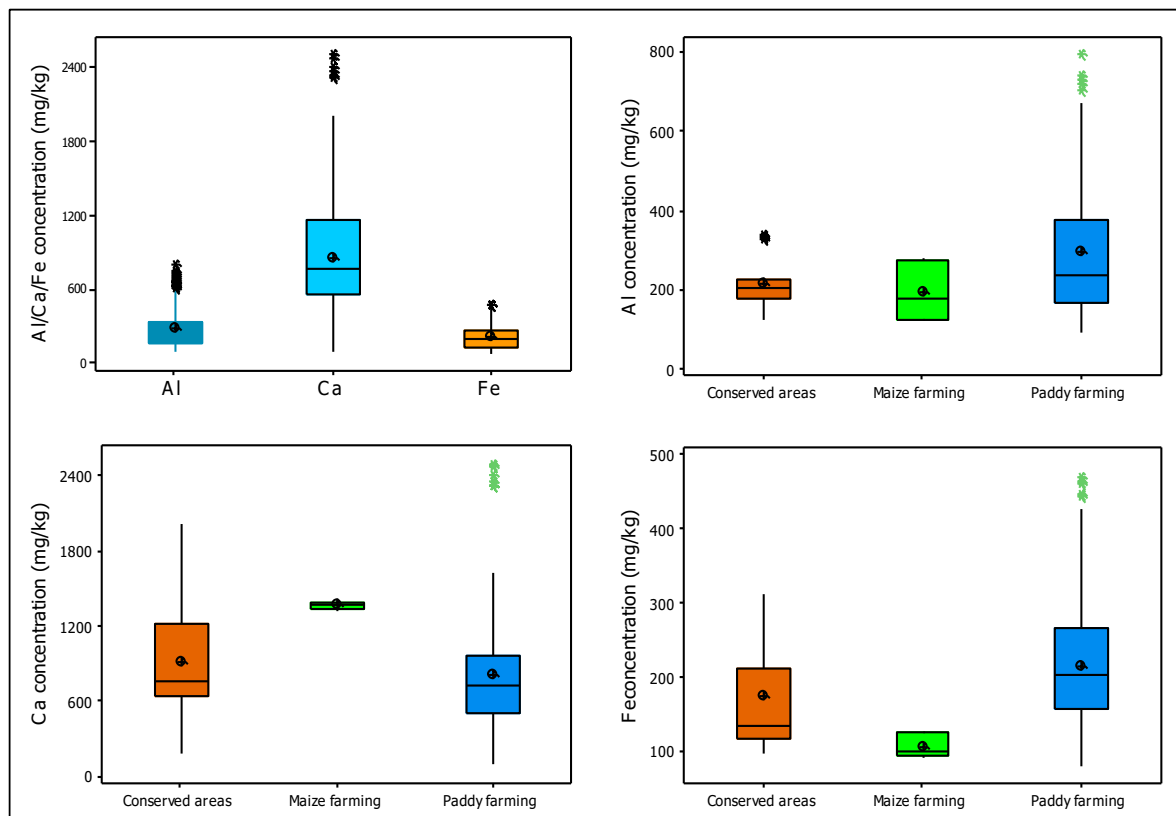
**Table 19: Soil nutrient concentration (in mg/kg dry wt) among schemes in Usangu agro-ecosystem**

	Irrigation Scheme	Al	Ca	Cu	Fe	K	Mg	Mn	P	S	Zn
Mean	Chimala	182.20	482.61	2.29	324.08	263.48	183.49	119.00	5.98	16.61	2.47
	Igalako	320.96	1420.45	0.55	182.80	432.36	253.80	159.10	10.94	23.20	1.97
	Ihahi	188.54	1060.09	0.81	158.31	579.64	215.31	226.91	17.56	21.39	3.38
	Ilaji	277.06	422.47	1.53	248.68	254.48	180.67	141.61	4.97	11.87	2.43
	Isenyela	210.72	755.58	0.31	107.89	263.75	101.30	147.85	6.35	23.35	1.46
	Kapunga	346.16	785.38	1.83	190.58	487.80	232.22	104.52	7.55	29.29	1.81
	Mabadaga	201.95	2387.82	2.11	155.81	241.27	1031.78	64.51	1.66	35.34	0.46
	Mahangole	287.42	1126.13	0.68	154.62	663.23	291.24	201.27	13.87	18.59	3.16
	Mubuyuni	285.44	452.71	3.44	288.81	146.88	196.03	98.92	4.44	12.38	2.02
	Uturo	199.15	811.53	4.14	245.48	284.13	339.29	171.84	6.57	19.64	2.95
95% CI mean lower bound	Chimala	179.64	468.69	2.01	319.29	257.38	178.66	118.79	5.55	14.65	2.15
	Igalako	204.83	882.49	0.36	154.06	299.13	221.43	134.60	5.60	14.42	1.25
	Ihahi	160.12	926.68	0.74	135.76	479.66	181.83	191.74	11.98	17.53	3.00
	Ilaji	226.65	226.99	0.40	189.12	133.33	126.24	39.83	2.12	6.12	1.95
	Isenyela	199.33	746.23	0.08	104.46	257.97	100.67	143.08	5.79	10.52	1.11
	Kapunga	304.94	716.34	1.63	174.67	421.22	215.33	90.00	6.19	23.51	1.63
	Mabadaga	186.97	2279.99	1.92	146.33	210.25	994.93	59.52	1.43	33.63	0.35
	Mahangole	204.91	943.30	0.54	139.27	582.15	257.71	172.12	6.98	15.37	2.45
	Mubuyuni	231.44	324.03	2.98	255.00	118.17	139.11	82.70	3.12	9.09	1.71
	Uturo	167.96	700.48	3.60	219.27	225.64	267.88	149.66	3.63	15.40	2.02
95% CI mean upper bound	Chimala	184.75	496.53	2.58	328.87	269.57	188.33	119.21	6.40	18.58	2.79
	Igalako	437.09	1958.40	0.74	211.53	565.58	286.16	183.59	16.27	31.98	2.68
	Ihahi	216.95	1193.50	0.88	180.87	679.62	248.78	262.07	23.14	25.25	3.76
	Ilaji	327.46	617.94	2.67	308.25	375.63	235.09	243.39	7.82	17.62	2.92
	Isenyela	222.11	764.93	0.55	111.32	269.53	101.93	152.62	6.92	36.18	1.81
	Kapunga	387.37	854.43	2.04	206.49	554.38	249.11	119.04	8.90	35.07	1.99
	Mabadaga	216.92	2495.66	2.31	165.29	272.29	1068.63	69.50	1.89	37.05	0.58
	Mahangole	369.93	1308.97	0.82	169.96	744.32	324.77	230.41	20.75	21.80	3.87
	Mubuyuni	339.44	581.38	3.91	322.61	175.59	252.95	115.15	5.77	15.66	2.34
	Uturo	230.34	922.58	4.68	271.70	342.62	410.70	194.01	9.51	23.89	3.87
Standard deviation	Chimala	2.26	12.30	0.25	4.24	5.39	4.27	0.19	0.37	1.74	0.28
	Igalako	177.75	823.42	0.29	43.98	203.92	49.54	37.49	8.17	13.44	1.09
	Ihahi	79.41	372.82	0.20	63.03	279.40	93.55	98.28	15.60	10.79	1.07
	Ilaji	63.00	244.30	1.42	74.45	151.41	68.02	127.20	3.57	7.19	0.61
	Isenyela	10.07	8.26	0.21	3.03	5.11	0.56	4.22	0.50	11.34	0.31
	Kapunga	170.84	286.21	0.86	65.94	275.96	69.99	60.18	5.62	23.96	0.73
	Mabadaga	13.24	95.29	0.17	8.37	27.41	32.56	4.41	0.21	1.51	0.10
	Mahangole	192.91	427.49	0.33	35.87	189.58	78.40	68.14	16.10	7.51	1.65
	Mubuyuni	165.30	393.91	1.42	103.49	87.90	174.25	49.66	4.06	10.06	0.97
	Uturo	61.63	219.44	1.06	51.80	115.58	141.10	43.82	5.81	8.38	1.83

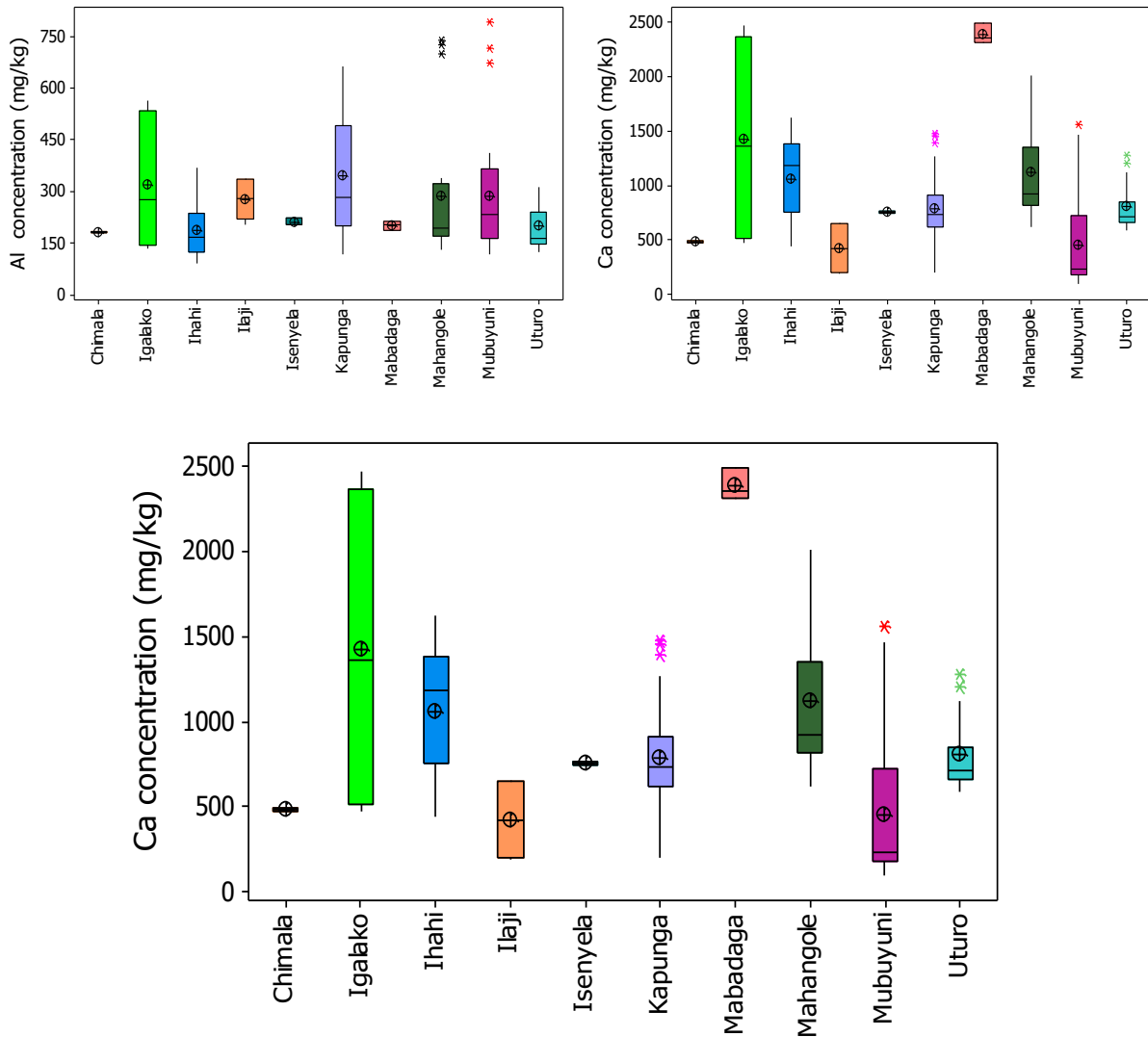
### (iii) Exchangeable Al, Fe, and Ca

The Al, Ca, and Fe concentrations were different between land use. Where “the overall Al, Ca, and Fe concentration trend found to be significantly greater in farming areas (maize and paddy) than conservation areas (Table 18 and Fig. 13). Fe and Ca concentration were higher in some conservation areas (Ca 919.65 and Fe 174.83 mg/kg) than maize (Fe 107.3 mg/kg and Ca

1362.55 mg/kg) and paddy farming areas (Fe 214.81 mg/kg and Ca 806.89 mg/kg). The spatial distribution of available Al, Fe, and Ca among irrigation schemes were highly variable (Fig. 13). Higher values were observed in Igalako, Mubuyuni, Mahongole, Uturo, Kapunga, and Ilaji irrigation schemes (Fig. 14 and Table 19). Ca and Fe concentrations are vital for plant growth because they are engaged in crucial plant biochemical activities, such as photosynthesis, but high Ca and Fe concentrations may limit plant nutrient availability, such as P, due to fixation. In the study area concentration of Al and Ca levels observed were within an acceptable range (1000 mg/kg) (Horneck *et al.*, 1999) for crop production and other nutrient availability. The available Fe was observed to be in the range of 81.14 to 470.5 mg/kg. The Fe concentration in UA was observed to be very high for plant uptake because were outside acceptable range of 0.3 to 10 mg/kg for crop production (Fig. 14 and Table 19)” (Mng’ong’o *et al.*, 2021).



**Figure 13: The Al, Ca, and Fe distribution in three land-use in UA soils**

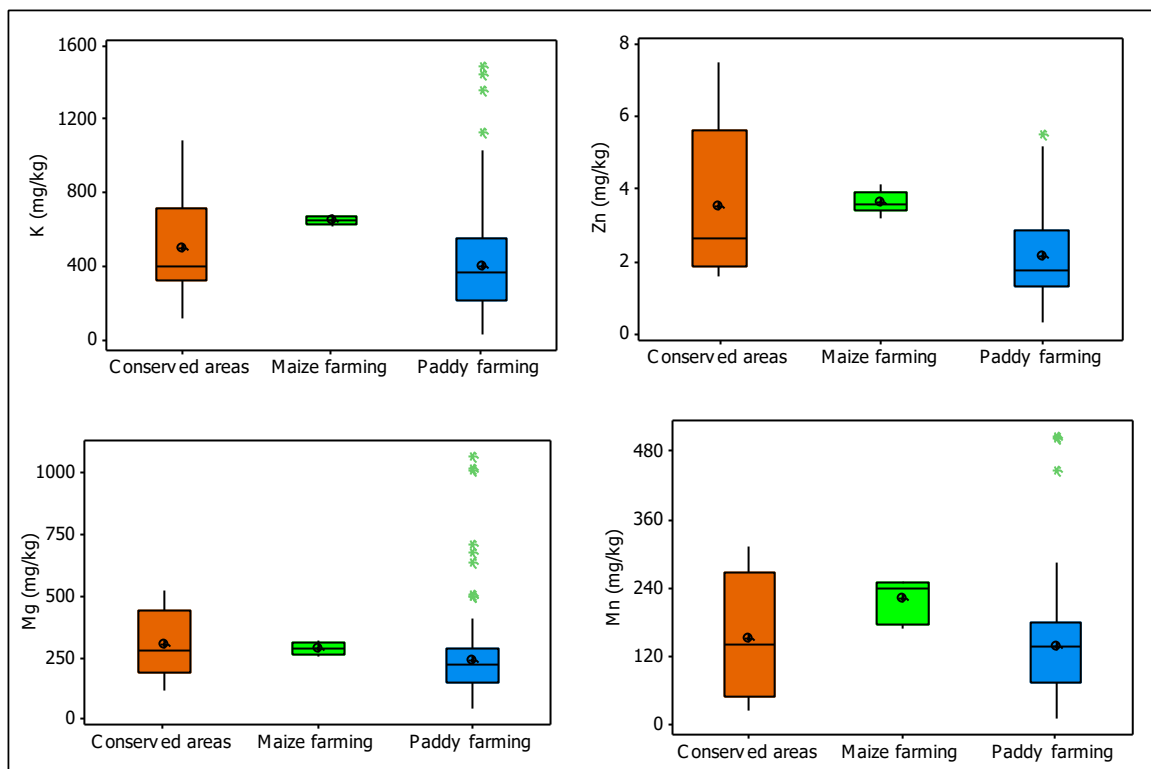


**Figure 14: The status of Al, Ca, and Fe in different schemes in Usangu agro-ecosystem, the cycle with + represents mean values**

**(iv) Extractable Mg, Zn, Mn, and K**

The K, Mg, Zn, and Mn concentrations in UA varied across land use and schemes (Table 18 and 19). The overall trend were K (28.75 to 1484.17 mg/kg) with mean value of 420.76 mg/kg, Mg (42.18 to 1069.21 mg/kg) with mean of 246.7 mg/kg, Zn (0.34 to 7.47 mg/kg) with mean value of 2.34 mg/kg while Mn concentration ranged 12.75 to 503.08 mg/kg with mean value of 142.43 mg/kg. The spatial Zn, Mg, K, and Mn distribution in UA varied between land use (Table 19 and Fig. 15), where higher K values determined in maize farming areas (647.11 mg/kg), followed by conservation areas (500 mg/kg) and paddy farming areas (400 mg/kg). A similar trend was followed by Mn and Zn, whilst higher concentration of Mg was found in conservation areas (301 mg/kg) than in maize (287 mg/kg) and paddy farming (239 mg/kg) areas.

The Mg:K ratio as estimate “of Mg and K availability for plant uptake, were observed to be less than 2, which is a recommended ratio for higher Mg and K availability to ensure optimal crop growth (Ndakidemi *et al.*, 2008). Therefore, Mg and K were in insufficiency level, constraining crop growth. In all soils studied, available Mn ranged from 3.0 to 384 mg/kg, “where the proposed deficiency level for Mn (DTPA) in the soil is 2.0 to 5.0 mg/kg, and values of greater than 140 mg/kg are regarded as excess” (Sillanpää, 1982). In this study, 5 sites (Igalako (159.10 mg/kg), Ihahi (226.91 mg/kg), Isenyela (147.85 mg/kg), Ilaji (141.61mg/kg) and Mahongole (201.27 mg/kg)), had excess Mn that can cause Mn toxicity in crops, and other five had deficient levels (Table 19). The concentration of available Zn in the study area soils were observed to be in a range of 0.34 to 7.47 mg/kg, which was above the suggested Zn range (0.4 to 0.6 mg/kg) for Zn deficiency” (Mng’ong’o *et al.*, 2021).



**Figure 15: Status and distribution of K, Zn, Mg, and Mn in different land use in Usangu agro-ecosystem.**

**(v) Total soil organic carbon (OC)**

The “organic carbon is a proxy for organic matter (OM), OM upon mineralization, releases different essential plant nutrients such as P, N, and S. More importantly, OC is essential for promoting and maintaining soil structure. Soils with higher OC tend to have better infiltration and are more robust against erosion. The total OC observed in the study area (Usangu agro-

ecosystem) were in the range of 0.37 to 2.37%, with a mean value of 1.51% (Table 17). Some irrigation schemes such as Ilaji (2.37%), Mabadaga (1.33%), Mahongole (1.37%), and Uturo (1.99%) found to have high OC than other schemes in UA, which recorded OC of less than 0.8%. As the range of OC determined was 0.37 to 2.37% (equivalent to 0.37-23.7 g/kg) where the critical threshold of soil organic carbon is 20.0 g/kg; therefore, OC determined in this study mostly was below recommended levels” (Mng’ong’o *et al.*, 2021).

#### **(vi) Total Nitrogen (Total N)**

The concentration of total N in studied soil samples ranged 0.29 to 1.73 g/kg and a mean value of 1.09 g/kg. All studied soil samples (198) had total N concentration less than 2.0 g/kg, a commended critical level (Ndakidemi & Semoka, 2006). However, some schemes had considerable total N concentration (g/kg) such as Ilaji (1.73), Uturo (1.65), Mabadaga (1.05), and Mahongole (1.10), whilst other schemes had total N below 0.29 g/kg (Table 17). It was found that most of the study area soils had total N in inadequate levels to sustain agricultural productivity.

#### **(vii) Micronutrients accumulation and distribution**

The study analyzed the availability of micronutrients such as Cr, Cu, Mo, Co, and Ni (Table 20 and 21) which are required for plant growth, but also considered PTEs at extreme concentrations as they are poisonous to plants and soil microbes.

**Copper (Cu):** The concentration of available Cu was observed to range from 0.03 to 7.21 mg/kg (Table 21). “For DTPA (Diethylenetriamine pentaacetate)-extractable Cu and which is highly correlated with M3-extractable Cu. Almost all soils studied had a Cu concentration above the proposed minimum limit (0.2 mg/kg) for crop productivity (Table 21). The concentration of Cu among land use were observed to vary significantly, such as conservation areas (0.15 to 3.67 mg/kg); maize farming (0.52 to 0.97 mg/kg); and paddy farming (0.03 to 7.21 mg/kg). The available Cu was observed to be high in paddy farming than in conservation and maize farming areas. The spatial distribution of Cu among irrigation schemes was observed to be significantly different ( $P < 0.05$ ), where the mean Cu concentration (in mg/kg) in different schemes were Ilaji (1.53), Kapunga (1.83), Mubuyuni (3.44), Uturo (4.14). Igalako (0.55), Isenyela (0.31), Mabadaga (2.11), Ihahi (0.81), and Mahongole (0.68). Where Ilaji, Mubuyuni, Chimala, Uturo, and Kapunga irrigation schemes (Fig. 16) were observed to have a higher copper content” (Mng’ong’o *et al.*, 2021).

**Cobalt (Co):** The concentration of Co determined in studied soils were 45.16 to 2684.3 µg/kg and mean value of 721.06 µg/kg. Among land use, Co were observed to be significantly different ( $P < 0.01$ ), such as; conservation areas (135.9 to 1523.9 µg/kg) and mean value of 634.29 µg/kg (Table 21, Fig. 16), maize farming (435.6 to 639.1 µg/kg) and mean value of 530.9 µg/kg, and in paddy farming (136.0 to 2684.3 µg/kg) with a mean value of 740.9 µg/kg. The spatial Co distribution over the study area was significantly different between schemes, where Ilaji (130.0 to 468.6 µg/kg), Chimala (667.0 to 719.3 µg/kg), Ihahi (164.2 to 1045.4 µg/kg), Igalako (365.4 to 883.5 µg/kg) (Table 21, Fig. 17) and other schemes as shown in Fig. 17 recorded higher Co values. The values found in this study were sufficient to allow plant growth; however, some sites had extremely high Co values, which likely potentially causing phytotoxicity effect to plants and microbial diversity in the soil.

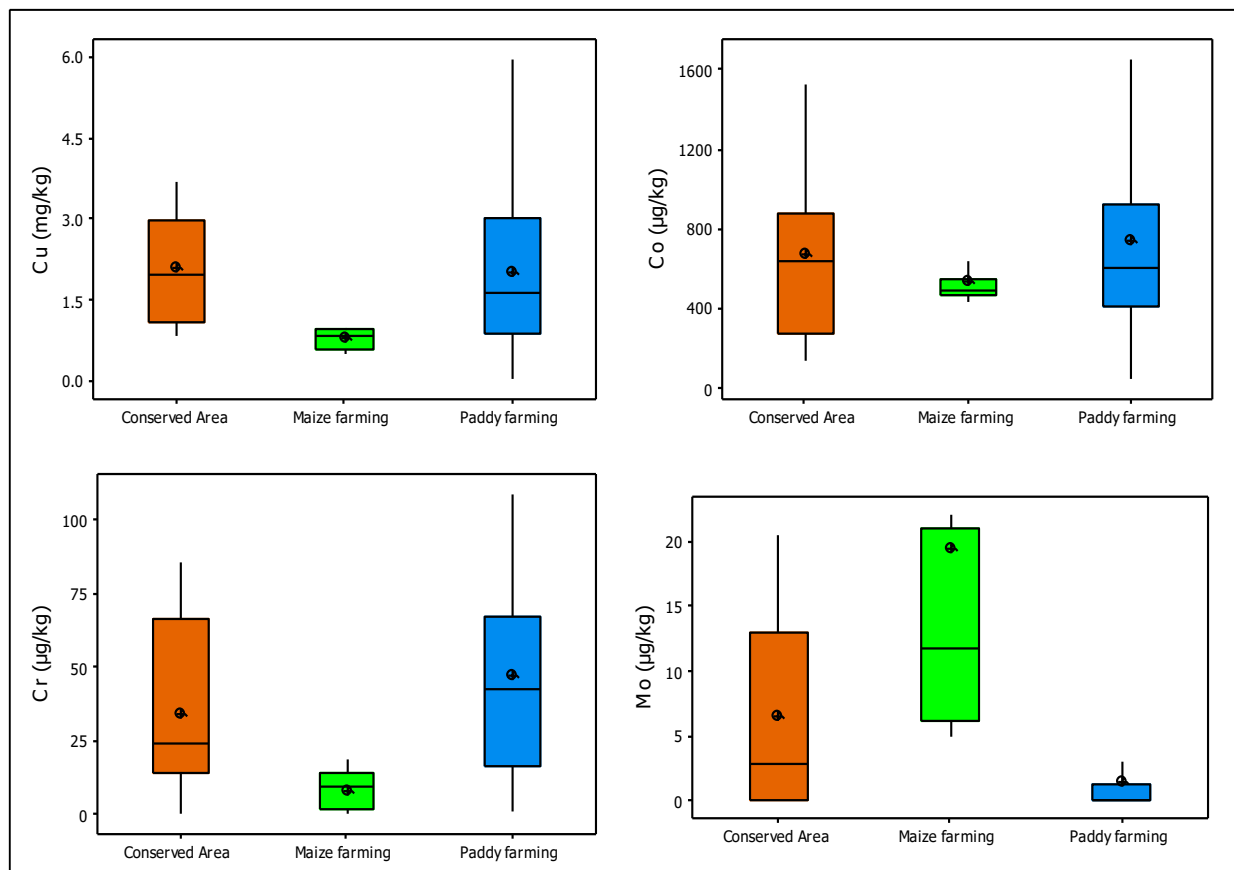
**Table 20: The soil micronutrients distribution in different irrigation schemes in Usangu agro-ecosystem in Southern Highland Tanzania (all concentrations are based on dry wt)**

	<b>Irrigation Scheme</b>	<b>Cu (mg/kg)</b>	<b>Co (µg/kg)</b>	<b>Cr (µg/kg)</b>	<b>Mo (µg/kg)</b>	<b>Ni (µg/kg)</b>
Mean	Chimala	2.29	699.57	101.46	ND	1086.71
	Igalako	0.55	572.35	26.14	2.25	244.42
	Ihahi	0.81	489.31	13.46	11.80	110.46
	Ilaji	1.53	291.19	46.08	ND	134.54
	Isenyela	0.31	325.74	6.09	16.44	93.28
	Kapunga	1.83	631.04	39.60	0.72	307.89
	Mabadaga	2.11	912.72	99.03	1.35	1770.17
	Mahangole	0.68	455.84	13.49	5.67	74.14
	Mubuyuni	3.44	987.06	84.92	0.18	1278.17
	Uturo	4.14	1619.78	55.81	3.45	799.26
95% CI mean lower bound	Chimala	2.01	667.11	89.51	ND	1048.17
	Igalako	0.36	420.93	15.58	0.28	114.61
	Ihahi	0.74	429.51	8.90	5.56	100.84
	Ilaji	0.40	167.11	18.80	ND	73.82
	Isenyela	0.08	318.78	1.02	14.51	83.99
	Kapunga	1.63	532.60	34.51	0.34	259.65
	Mabadaga	1.92	802.37	92.48	0.55	1658.89
	Mahangole	0.54	400.64	9.32	1.75	63.86
	Mubuyuni	2.98	871.61	69.46	0.00	942.91
	Uturo	3.60	1334.59	51.30	1.20	662.69
95% CI mean upper bound	Chimala	2.58	732.03	113.41	ND	1125.25
	Igalako	0.74	723.78	36.70	4.21	374.23
	Ihahi	0.88	549.10	18.03	18.05	120.08
	Ilaji	2.67	415.26	73.35	ND	195.26
	Isenyela	0.55	332.71	11.16	18.37	102.57
	Kapunga	2.04	729.49	44.69	1.10	356.12
	Mabadaga	2.31	1023.07	105.59	3.25	1881.45
	Mahangole	0.82	511.05	17.65	9.59	84.43
	Mubuyuni	3.91	1102.52	100.39	0.35	1613.43
	Uturo	4.68	1904.98	60.32	5.70	935.83
Standard deviation	Chimala	0.25	28.69	10.56	0.00	34.06
	Igalako	0.29	231.78	16.16	3.01	198.70
	Ihahi	0.20	167.09	12.75	17.45	26.88
	Ilaji	1.42	155.07	34.09	0.00	75.88
	Isenyela	0.21	6.15	4.48	1.70	8.21
	Kapunga	0.86	408.06	21.09	1.57	199.94
	Mabadaga	0.17	97.52	5.80	1.68	98.34
	Mahangole	0.33	129.08	9.74	9.16	24.05
	Mubuyuni	1.42	353.43	47.34	0.54	1026.33
	Uturo	1.06	563.56	8.92	4.45	269.86

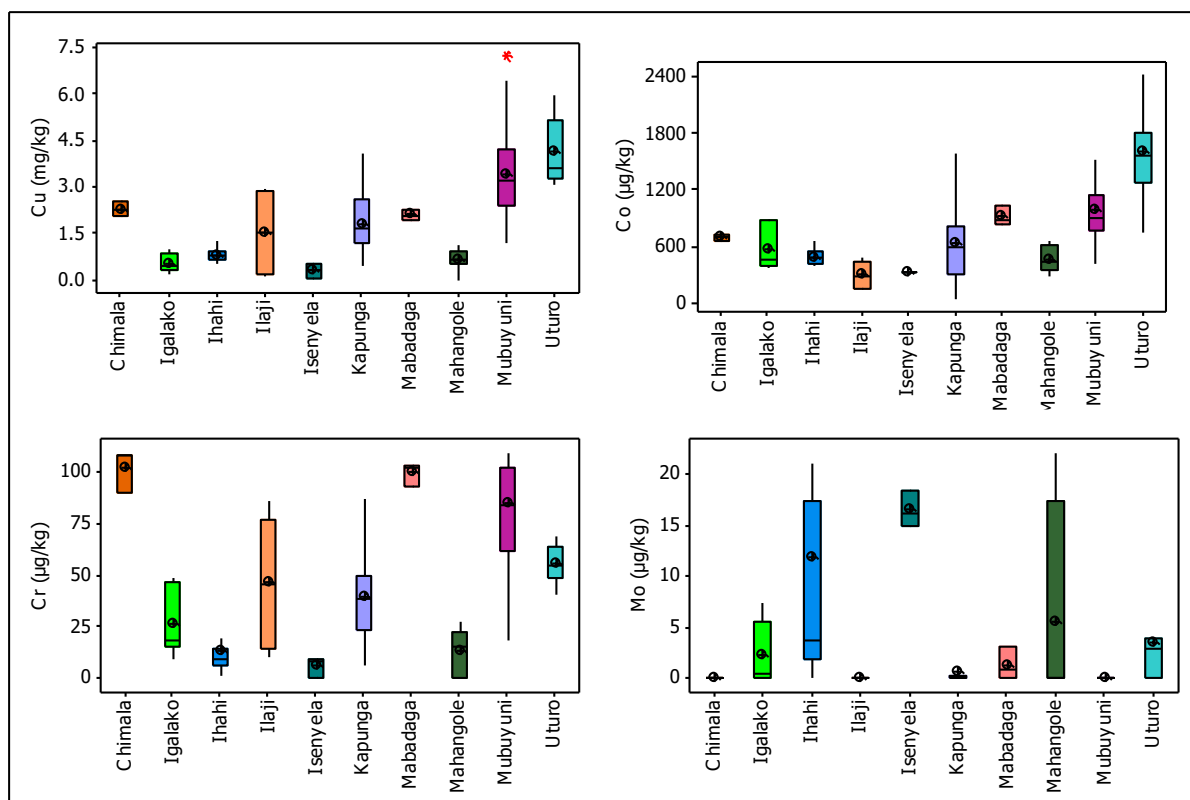
*ND; means not detected; their concentration were below detection limits*

**Table 21: The soil micronutrients distribution in different land uses in Usangu agro-ecosystem (all concentrations are based on dry wt)**

	Land Use	Cu (mg/kg)	Co ( $\mu\text{g}/\text{kg}$ )	Cr ( $\mu\text{g}/\text{kg}$ )	Mo ( $\mu\text{g}/\text{kg}$ )	Ni ( $\mu\text{g}/\text{kg}$ )
Mean	Conserved areas	1.78	634.29	30.72	5.45	320.38
	Maize farming	0.70	530.85	5.47	15.18	109.07
	Paddy farming	2.03	740.91	46.81	2.53	535.17
95% CI mean lower bound	Conserved areas	1.24	423.68	18.28	2.07	186.83
	Maize farming	0.59	481.22	0.97	10.63	74.63
	Paddy farming	1.81	668.02	41.10	1.22	429.29
95% CI mean upper bound	Conserved areas	2.31	844.91	43.17	8.83	453.93
	Maize farming	0.82	580.48	9.98	19.73	143.51
	Paddy farming	2.26	813.79	52.53	3.84	641.06
Standard deviation	Conserved areas	1.17	455.90	26.94	7.32	289.09
	Maize farming	0.17	75.97	6.90	6.96	52.72
	Paddy farming	1.49	477.70	37.46	8.56	693.96



**Figure 16: The soil micronutrients distribution among land use in Usangu agro-ecosystem, the cycle with + represents mean values**



**Figure 17: The soil micronutrients distribution among schemes in Usangu agro-ecosystems**

The available Cr, Mo, and Ni: The available Cr, Mo, and Ni concentrations ( $\mu\text{g}/\text{kg}$ ) determined were Ni (25.22 to 4497.32), Cr (0.00 to 222.78), and Mo (0.00 to 65.87) across land use and irrigation schemes in UA (Table 20). The study observed that “among schemes with a higher Cr concentration ( $\mu\text{g}/\text{kg}$ ) determined were Mabadaga (99.03), Kapunga (39.60), Mubuyuni (84.92), Uturo (55.81), and Ilaji (46.08) (Table 20). At the same time, Mo was higher (in  $\mu\text{g}/\text{kg}$ ) in Ihahi (11.80), Isenyela (16.44), and Mahongole (5.67). For Ni, higher values were observed to be greater than 74.14  $\mu\text{g}/\text{kg}$ . The Cr, Ni, and Mo concentration were found to vary among soils from different land use as higher Cr concentration ( $\mu\text{g}/\text{kg}$ ) determined in conservation areas (0.01 to 85.74 and mean value of 30.72), and paddy farming (0.95 to 222.78 and mean value 46.81) than maize farming areas (0.01 to 18.50 and mean value of 5.47). Higher values of Mo determined in maize farming areas (5.00 to 22.11  $\mu\text{g}/\text{kg}$ ) and in conservation areas (0.0 to 20.39  $\mu\text{g}/\text{kg}$ ), than paddy farming areas (0.01 to 65.87  $\mu\text{g}/\text{kg}$ ) and where a similar trend determined for Ni (Table 21)” (Mng’ong’o *et al.*, 2021).

#### **4.1.2. Current soil phosphate status and its availability to plants in Usangu agro-ecosystem**

##### **(i) Total soil phosphate (TP) in Usangu agro-ecosystem**

The determined TP concentration in agricultural soils were observed to vary among irrigation schemes and land use in UA (Table 22 and 23). The concentration of TP determined in the study area were 63.12 to 1350.09 mg/kg, which varied among land use, whereas; TP in conservation areas were 129.54 to 589.63 mg/kg; in paddy farming TP was 63.12 to 1350.9 mg/kg, and maize farming areas 553.26 to 668.46 mg/kg (Table 22 and 23). It was found that farming areas had higher TP compared with conservation areas. The TP spatial distribution in UA varied significantly among schemes (Table 22), where some schemes had higher TP concentration (mg/kg) such as Kapunga (1350.9), Mahongole (814.3), Ihahi (790.7), Ilaji (589.6), Uturo (556.1), Igalako (536.1), and Mubuyuni (435.1). But also, the study found that schemes or land use that had a high Ca, Al, Mg, and Fe concentration were observed to have high TP (Table 22). On the other hand, TP in agricultural soils in Mabadaga (203.47 mg/kg), Chimala (177.99 mg/kg), and Isenyela (138.07 mg/kg) were found to be low (Table 22).

**Table 22: The concentration of total P, bioavailable P (B-P), and complexed P (Po), P bioavailability determinants, concentration per cent of P availability in soils from different land use in Usangu agro-ecosystem (all concentrations based on dry wt)**

	Land Use	Al (mg/kg)	Ca (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Total P (mg/kg)	B-P (mg/kg)	Po (mg/kg)	%Po	% P Bioavailability
Mean	Conservation areas	214.91	919.65	174.83	300.97	347.26	13.49	333.77	96.12	3.88
	Maize farming	193.59	1362.55	107.03	286.87	468.57	25.73	442.84	94.51	5.49
	Paddy farming	294.10	806.89	214.81	238.59	316.86	7.70	309.16	97.57	2.43
Minimum	Conservation areas	125.36	194.82	97.90	115.99	129.54	0.99	128.55	99.24	0.76
	Maize farming	124.87	1318.56	91.64	253.49	353.26	15.20	338.06	95.70	4.30
	Paddy farming	93.21	95.10	81.14	42.18	63.12	0.52	62.60	99.18	0.82
Maximum	Conservation areas	337.51	2010.72	314.08	520.20	589.63	35.79	553.84	93.93	6.07
	Maize farming	278.21	1415.24	127.75	316.90	668.46	40.32	628.14	93.97	6.03
	Paddy farming	792.97	2494.35	470.59	1069.21	1350.90	49.87	1301.03	96.31	3.69

**Table 23: The concentration of total P, bioavailable P (B-P), and complexed P (Po), P bioavailability determinants, concentration per cent of P availability in soils from irrigation schemes in Usangu agro-ecosystem (all concentrations based on dry wt)**

	<b>Scheme</b>	<b>Al (mg/kg)</b>	<b>Ca (mg/kg)</b>	<b>Fe (mg/kg)</b>	<b>Mg (mg/kg)</b>	<b>B-P (mg/kg)</b>	<b>Total P (mg/Kg)</b>	<b>Po (mg/kg)</b>	<b>%Po</b>	<b>% P bioavailability</b>
Mean	Chimala	182.19	482.61	324.08	183.49	5.98	170.43	164.45	96.49	3.51
	Igalako	320.96	1420.45	182.79	253.80	10.94	384.24	373.30	97.15	2.85
	Ihahi	188.54	1060.09	158.31	215.31	17.56	417.26	399.70	95.79	4.21
	Ilaji	277.06	422.47	248.68	180.66	4.97	354.35	349.38	98.60	1.40
	Isenyela	210.72	755.58	107.89	101.30	6.35	115.45	109.10	94.50	5.50
	Kapunga	346.16	785.38	190.58	232.22	7.55	349.69	342.14	97.84	2.16
	Mabadaga	201.95	2387.82	155.81	1031.78	1.66	172.88	171.22	99.04	0.96
	Mahangole	287.42	1126.13	154.62	291.24	13.87	374.96	361.09	96.30	3.70
	Mubuyuni	285.44	452.71	288.81	196.03	4.44	227.27	222.83	98.05	1.95
	Uturo	199.15	811.53	245.48	339.29	6.57	333.73	327.16	98.03	1.97
Maximum	Chimala	184.30	495.60	326.97	188.39	6.22	177.99	171.77	96.51	3.49
	Igalako	563.72	2467.91	235.18	296.31	22.10	536.11	514.01	95.88	4.12
	Ihahi	367.55	1627.17	289.54	409.10	49.87	790.72	740.85	93.69	6.31
	Ilaji	337.51	654.66	314.08	245.43	8.39	589.63	581.24	98.58	1.42
	Isenyela	222.35	762.25	111.38	101.86	6.93	138.07	131.14	94.98	5.02
	Kapunga	662.23	1481.94	321.60	334.16	21.50	1350.90	1329.40	98.41	1.59
	Mabadaga	214.83	2494.35	165.35	1069.21	1.86	203.47	201.61	99.09	0.91
	Mahangole	739.25	2010.72	197.24	445.81	40.32	814.33	774.01	95.05	4.95
	Mubuyuni	792.97	1558.84	470.59	707.26	15.89	435.11	419.22	96.35	3.65
	Uturo	312.28	1274.94	332.93	520.20	18.02	556.11	538.09	96.76	3.24

### **(ii) Soil bioavailable P (B-P) in Usangu agro-ecosystem**

The amount of P which is readily available P for plant uptake in agricultural soils in the UA determined by M3 method was in the range of 0.52 to 49.87 mg/kg. The determined “B-P among land use (conservation areas, paddy and maize farming areas) were; conservation areas (1.0 to 35.8 mg/kg), maize farming areas (15.2 to 40.3 mg/kg) and paddy farming areas (0.5 to 49.9 mg/kg). Bioavailable P concentrations (B-P) in agricultural soils in UA ranged from 0.52 to 49.87 mg/kg (Table 22), with differences between land use and irrigation systems (Table 22 and 23). The study found that maize farming areas (15.20 to 40.32 mg/kg) and paddy farming areas (0.52 to 49.9 mg/kg) had highest B-P concentrations ranges than conservation areas (0.99 to 35.79 mg/kg) among land use (maize, paddy, and conservation areas). However, the mean B-P concentration was very low in farming areas, especially in paddy farming areas (7.70 mg/kg) compared with maize farming areas (25.73 mg/kg) and conservation areas (13.49 mg/kg). Higher Mg, Al, Ca, and Fe concentrations were found to be associated with reduced B-P. The paddy farming areas which had a higher Fe (806.89 mg/kg), Ca (214.81 mg/kg), Al (294.1 mg/kg), and Mg (238.59 mg/kg) concentration were found to have low B-P. Furthermore, negative correlations were determined between Al, Fe, Ca, and Mg and determined B-P (Table 24). The study evidenced that some schemes, had higher B-P concentrations (mg/kg (maximum values)) such as Ihahi (49.0), Mahongole (40.32), Igalako (22.10), Kapunga (21.5), Mubuyuni (18.55), and Uturo (18.02) (Table 23). The determined values were in range of optimal (26-35 mg/kg) to higher (36-45 mg/kg) for crop requirements in the area (Mallarino *et al.*, 2013), where other irrigation schemes, such as Mabadaga, Chimala, Isenyela, and Ilaji found B-P to be insufficient in agricultural soils because the determined values were less than 8.39 mg/kg” (Mng’ong’o *et al.*, 2021).

### **(iii) The P bioavailability among land use**

The concentration of phosphorus in agricultural soils from various land use in the study area revealed a substantial difference in the amount of phosphorus contained in soil samples compared with the amount available for plant absorption among land use (Table 22 and 23). From TP and B-P determined, the P concentration unavailable for plant uptake, due to either fixation or complexation by metals, obtained by subtracting B-P from TP. In this dissertation, this amount was designated as complexed P (Po). The TP and B-P comparison among land-use found that Po was very high (more than 90% of TP), showing that B-P concentration was very low compared with TP determined (Table 22 and 23). The TP and B-P concentration (mg/kg)

determined among three land use were; Paddy farming areas (TP=63.12 to 1350.09, B-P=0.52 to 49.87); Maize farming areas (TP=353.26 to 668.46, B-P=15.20 to 40.32); and Conservation areas (TP=129.54 to 589.69, B-P=0.93 to 35.79) (Table 22). Higher values of TP in paddy and maize farming areas and very low bioavailable P (0.82 to 6.03% of the TP) show that paddy and maize farming activities negatively influenced P availability in agro-ecosystem. The situation was observed in paddy farming areas in the study area, although the same land use were observed to have the highest TP values. Paddy farming areas were observed to have higher Po (62.60 to 1301.03 mg/kg) and lower per cent of P bioavailability (0.82 to 3.69%) compared with conservation areas (0.72 to 6.07%) and maize farming areas (4.30 to 6.03%) (Table 22). The B-P spatial distribution and per cent P bioavailability were observed to vary significantly between schemes (Table 23). The general trend of per cent P bioavailability ranged from 0.91 to 6.31%. Where high P bioavailability were found in Ihahi (6.32%), Isenyela (5.02%), Mahongole (4.95%), and Igalako (4.12%). Nevertheless, some schemes documented a very low B-P per cent compared with TP determined, such as Kapunga (1.59%), Ilaji (1.42%), and Mabadaga (0.91%). This study found that farming areas with high Al, Ca, Fe, and Mg concentrations had a significant positive correlation with TP but negatively correlated with B-P (Table 24).

**Table 24: The correlation coefficient for T-P, B-P, Al, Ca, Fe, and Mg concentration (mg/kg) in soils from Usangu agro-ecosystem**

	Al	Ca	Fe	Mg	B-P	T-P
Al	1					
Ca	0.35***	1				
Fe	0.34***	0.23**	1			
Mg	-0.04	0.45***	0.47***	1		
B-P	-0.37***	-0.18*	-0.06	-0.23**	1	
T-P	0.09	0.11	0.76***	0.28***	1.00***	1

*The correlation coefficient with an asterisk (\*) is statistically significantly different at \* $P < 0.05$ , \*\* $P < 0.01$ , and \*\*\*  $P < 0.001$ .*

Locations with high  $Al_{M3}$  and  $Fe_{M3}$  concentrations had lower available  $P_{M3}$  concentrations, but there was also a significant negative association between Al and Fe and available  $P_{M3}$  ( $P < 0.05$ ). The  $P_{M3}$  concentration among irrigation schemes was observed to significantly increase with a decrease in altitude ( $P < 0.05$ ,  $R^2 = 0.36$ ). The ratio of  $P_{M3}/(Al_{M3} + Fe_{M3})$ , which estimates the availability of  $P_{M3}$  for plant uptake, was found to range from 0.004 to 0.16, with values “ranging

from below optimum ( $P_{M3}/(Al_{M3}+Fe_{M3}) < 0.06$ , optimum ( $P_{M3}/(Al_{M3}+Fe_{M3})$ ) 0.06 to 0.11, and above optimum  $P_{M3}/(Al_{M3}+Fe_{M3}) > 0.15$ ” (Sims *et al.*, 2002).

#### **4.1.3. Soil phosphate sorption capacity (PSC) and phosphate saturation degree (PSD) indicator as estimate for risk of P fixation and desorption in UA**

##### **(i) P sorption and sorption capacity**

The M3 data were used to evaluate the ability of the soil to adsorb or fix P (PSC) in various irrigation schemes and land use in Usangu agro-ecosystem (Guo, 2009b; Kleinman & Sharpley, 2002). The study discovered that soil PSC differed according to land use and schemes (Table 25). The “common P adsorbent ( $Al_{M3}$  and  $Fe_{M3}$ ) in acidic soils ranged 5.6 to 34.9 mmol/kg, with a mean value of 14.1 mmol/kg. PSC was found to be greater in agricultural regions, such as paddy farming areas (5.6 to 34.9 mmol/kg) with a mean value of 14.8 mmol/kg and maize farming areas (6.3 to 12.6 mmol/kg) with a mean value of 9.1 mmol/kg), compared with PSC in conservation areas, which was found to be lower than 9.1 mmol/kg. Higher Ca concentrations in the research study areas are shown by high PSC values based on  $Ca_{M3}$  (Table 25 and 26).  $Ca_{M3}$  and  $PSC_{M3}$  had a positive correlation ( $P < 0.001$ ,  $R^2 = 0.43$ ), indicating that  $Ca_{M3}$  had a strong influence on P sorption and availability in the studied soils. On the other hand, positive correlations were found between  $Al_{M3}$  ( $P < 0.001$ ,  $R^2 = 0.36$ ) and  $Fe_{M3}$  ( $P < 0.001$ ,  $R^2 = 0.24$ ) and  $PSC_{M3}$  in the study area. As an alternate method of estimating the PSC, the ratio of  $P_{M3}$  and  $Al_{M3}$  was in the range of 3.32 to 12.35, with greater values in farming regions than in conservation zones (Table 25 and 26). The spatial distribution of determined PSC (in mmol/kg) among irrigation scheme in UA were found to vary significantly in the study area. The mean observed PSC values (mmol/kg) among irrigation schemes were Mubuyuni (15.8), Igalako (15.2), Ilaji (14.7), Mahongole (13.4), Chimala (12.6), Uturo (11.8), Ihahi (9.8), and Isenyela (9.7) (Table 27)” (Mng’ong’o *et al.*, 2021).

**Table 25: The concentration of Ca, Al, Fe, and P, estimated PSC (mmol/kg), PSD (%) and maximum sorption capacity (mmol/kg) in soils among irrigation schemes in Usangu**

Irrigation Scheme	Al	Ca	Fe	P	PSC (Al+Fe)	PSD (Al+Fe)	Al/Fe	Max sorption	M3 (P <sub>M3</sub> /(Al <sub>M3</sub> +Fe <sub>M3</sub> ))
	mmol/kg					%		mmol/kg	
Chimala	6.75	12.04	5.8	0.19	12.56	1.54	1.16	49.2	0.01
Igalako	11.9	35.44	3.27	0.35	15.17	2.72	3.83	101.22	0.05
Ihahi	6.99	26.45	2.83	0.57	9.82	6.77	2.48	72.55	0.16
Ilaji	10.27	10.54	4.45	0.16	14.72	1.00	2.37	50.53	0.01
Isenyela	7.81	18.85	1.93	0.21	9.74	2.1	4.04	57.19	0.02
Kapunga	12.83	19.6	3.41	0.24	16.24	1.8	4.52	71.68	0.06
Mabadaga	7.48	59.58	2.79	0.05	10.27	0.52	2.68	139.71	0.00
Mahangole	10.65	28.1	2.77	0.45	13.42	5.11	3.92	83.04	0.14
Mubuyuni	10.58	11.3	5.17	0.14	15.75	1.12	2.19	54.09	0.03
Uturo	7.38	20.25	4.4	0.21	11.78	2.05	1.67	64.05	0.05

**Table 26: The PSC (mmol/kg) and PSD (%) estimated in soils from different land use in Usangu agro-ecosystem**

	Land Use	Al	Fe	Ca	P	PSC (Al+Fe)	PSC (Ca)	PSD (Al+Fe)	PSD (Ca)	PSD (P <sub>M3</sub> /Al <sub>M3</sub> )	Max sorption
		mmol/kg				mmol/kg		%			mmol/kg
Mean	Conserved areas	7.97	3.13	22.95	0.44	11.10	22.95	4.47	2.18	6.16	68.09
	Maize farming	7.18	1.92	34.00	0.83	9.09	34.00	9.60	2.44	12.35	86.18
	Paddy farming	10.90	3.85	20.13	0.25	14.75	20.13	2.28	1.51	3.32	69.76
Minimum	Conserved areas	4.65	1.75	4.86	0.03	7.92	4.86	0.26	0.20	0.37	45.62
	Maize farming	4.63	1.64	32.90	0.49	6.30	32.90	5.53	1.40	6.73	78.50
	Paddy farming	3.46	1.45	2.37	0.00	5.62	2.37	0.01	0.01	0.01	24.34
Maximum	Conserved areas	12.51	5.62	50.17	1.16	18.10	50.17	12.71	5.56	15.92	118.43
	Maize farming	10.31	2.29	35.31	1.30	12.60	35.31	15.48	3.85	19.67	93.55
	Paddy farming	29.39	8.43	62.24	1.61	34.85	62.24	17.58	13.63	25.00	172.35

## **(ii) P saturation degree (PSD) and P loss to the environment**

The PSD as an agro-environmental indicator, phosphate saturation degree (PSD), can be used to assess the quantity of soil P accessible and the amount of additional P that can be supplied to the soil for safe storage and availability to plants before excess P starts leaking into surface and ground waters. The estimated PSD in UA ranged 0.01 to 17.6%, with a mean value of 2.8% (Table 25). As an alternate measure of P saturation, the  $P_{M3}$  to  $Al_{M3}$  ratio was calculated and found to be in the range of 0.01 to 25.0%, with a mean of 4.0%. Based on all of this, the soil in Usangu agro-ecosystem was unsaturated or had unsaturated P status (mean  $PSD_{M3}$  was less than 24%) (Van Meirvenne *et al.*, 2007). The Al/Fe and Fe/Al ratios were found to have a negative and positive connection with the soil's PSD, respectively. Furthermore, Al and Fe concentrations in the study area had a strong negative correlation ( $P < 0.01$ ,  $R^2 = 0.57$  and  $P < 0.01$ ,  $R^2 = 0.42$ , respectively) with the PSD of the soil.

The study observed variation in estimated PSD among land uses where paddy farming areas had PSD of 0.01 to 17.6%, maize farming areas (5.5 to 15.5%), while the conservation areas had PSD of 0.3 to 12.7%. Moreover, PSD in the study area were found to be slightly different among irrigation schemes, where higher PSD values were observed in Ihahi (17.6%), Mahongole (15.5%), Uturo (6.2%), Igalako (5.7%), Kapunga (5.8%), Mubuyuni (3.8%), Chimala (1.6%), Ilaji (1.5%), and Mabadaga (0.6%) (Table 25). This was in line with the determined  $Al_{M3}$ ,  $Fe_{M3}$ , and  $Ca_{M3}$  concentration, which determines PSC and important parameters in determination of PSD. Among 10 studied irrigation schemes, 5 schemes had higher PSD values (i.e., Ihahi (17.6%), Mahongole (15.5%), Uturo (6.2%), Igalako (5.7%), Kapunga (5.8%)), which can possibly lead to high P loss risk to water bodies through leaching, surface runoff and soil erosion. The maximum P sorption computed by considering  $Al_{M3}$ ,  $Ca_{M3}$ , and  $Fe_{M3}$  concentrations were in range of 24.3 to 172.4 mmol/kg (Table 25 and 26), where all observed values were above determined PSC, thus more capacity to adsorb more P.

## **(iii) The correlation of PSC and PSD to crop productivity**

Due to the fact that availability of P for plant uptake is determined by PSC and PSD of agricultural soils, consequently, PSC and PSD can influence crop productivity by determining P availability to plants and losses (Schoumans *et al.*, 2014). As a result, soils with low PSC are more likely to lose P to the environment, making P unavailable for plant uptake while also damaging water reservoirs. However, higher PSC can fix all added P and making it inaccessible

for plant uptake due to Al and Fe complexation (Barrow *et al.*, 2020). In Usangu agro-ecosystem, higher PSC (in mmol/kg) were determined in Mubuyuni (17.8), Kapunga (16.2), Igalako (15.2), Mahongole (13.4), and Uturo (11.8), while lower PSC determined in Ilaji, Mabadaga, and Ihahi (Table 25). Since P is linked to a solid phase and partially available to the soil solution via pseudo-equilibrium desorption processes, increased PSC lowers P loss and leaching to surface runoff and water bodies. For that reason, it increases P available for agricultural uptakes for higher yields.

In the research study area, the ratio of  $P_{M3}$  to  $Al_{M3}$  and  $Fe_{M3}$  (M3) was calculated to assess the amount of P accessible for plant uptake. Where “the ratio of  $P_{M3}$  to  $Al_{M3}$  and  $Fe_{M3}$  (M3) is divided into three groups: i) M3 below 0.06 indicates that the availability of P for plant uptake is below optimum, ii) M3 0.06 to 0.11 indicates that P availability for plant uptake is optimum, and P addition is rarely recommended, and iii) M3 larger than 0.11 indicates that P availability for plant uptake is above optimum and soil P will not limit crop yield” (Mallarino *et al.*, 2013). In the study area, the M3 was observed to range from 0.00016 to 0.16 (Table 24), where most studied irrigation schemes had M3 below optimum to optimum group. In contrast, few soils from Ihahi and Mahongole irrigation schemes had M3 greater than 0.11, which corresponds to above optimum, indicating that any P addition will likely speed up the risk of P loss from agricultural fields to water resources, making P fertilization uneconomical, despite of increasing production cost.

#### **(iv) PSC and PSD as an agro-environmental indicators**

Management of agricultural soils and environmental quality monitoring in agro-ecosystem can be determined by PSC and PSD indicators serving as agro-environmental indicators. The PSD calculates how much more P can be added to the soil before P desorption and nutrient loss becomes an environmental concern. From the analysis, “the approximated PSD has been utilized to quantify P concentration in agricultural runoffs and irrigation channels due to the fact that a strong correlation between PSD and P concentration in runoffs has been reported. The estimated PSD in the research area was less than 24%, showing that most places had unsaturated P status; nevertheless, Ihahi and Mahongole found to have higher PSD (12.7 to 17.6%), indicating that P loss and eutrophication could be a potential threat. In the study area, soils were observed to have PSC ranging from low to high PSC, i.e., 6.3 to 34.9 mmol/kg (Table 24), which corresponds to high to low P loss to the environment (Bortoluzzi *et al.*, 2015). Furthermore, a strong positive correlation ( $P < 0.001$ ,  $R^2 = 0.79$ ) was observed between P

in agricultural soils and P in water samples (rivers and drainages channels) in the study area; this indicates the influence of P loss from agricultural fields to water resources” (Mng’ong’o *et al.*, 2021).

**(v) Sorption and desorption of phosphate in soils of Usangu agro-ecosystem**

The result of the studied parameters is shown in Table 27 to Table 30 and Fig. 18, where the detailed description of studied parameters in Subsection 4.2

**Table 27: The general descriptive statistics on chemical soil properties of the soil samples used in batch sorption and desorption experiment from the Usangu agro-ecosystem**

Soil properties	Minimum	Median	Maximum	Mean	SD
C (g/kg)	7.87	15.65	32.44	16.13	5.59
Fe <sub>ox</sub> (mmol/kg)	9.45	75.13	131.54	78.45	36.91
Al <sub>ox</sub> (mmol/kg)	12.19	20.65	53.28	25.51	11.16
PSC (mmol/kg)	16.70	54.14	79.55	51.98	18.12
P <sub>ox</sub> (mmol/kg)	3.24	11.42	14.76	10.33	3.82
pH <sub>KCl</sub>	4.60	5.05	7.43	5.28	0.72

**Table 28: The P concentration remaining in soil solution and P adsorbed in soil colloids in a batch sorption experiment with different initial P concentrations (n = 15)**

Initial P added (mg/L)	CP (Final P in solution, (mg/L))				Q (P adsorbed to soil colloids, mg/kg)			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
0.0	0.029	0.032	0.000	0.123	0.000	0.000	0.000	0.000
0.1	0.052	0.043	0.000	0.200	1.373	0.781	0.000	2.600
0.5	0.140	0.062	0.006	0.289	9.365	1.609	5.490	12.834
1.0	0.360	0.088	0.171	0.507	16.631	2.287	12.809	21.546
2.0	0.836	0.183	0.377	1.429	30.269	4.749	14.853	42.205
5.0	2.622	0.603	0.993	4.776	61.821	15.678	5.826	104.189
7.5	6.395	0.894	4.666	8.377	29.959	21.027	0.000	73.684
10.0	9.189	1.093	6.061	11.698	24.557	23.170	0.000	102.406

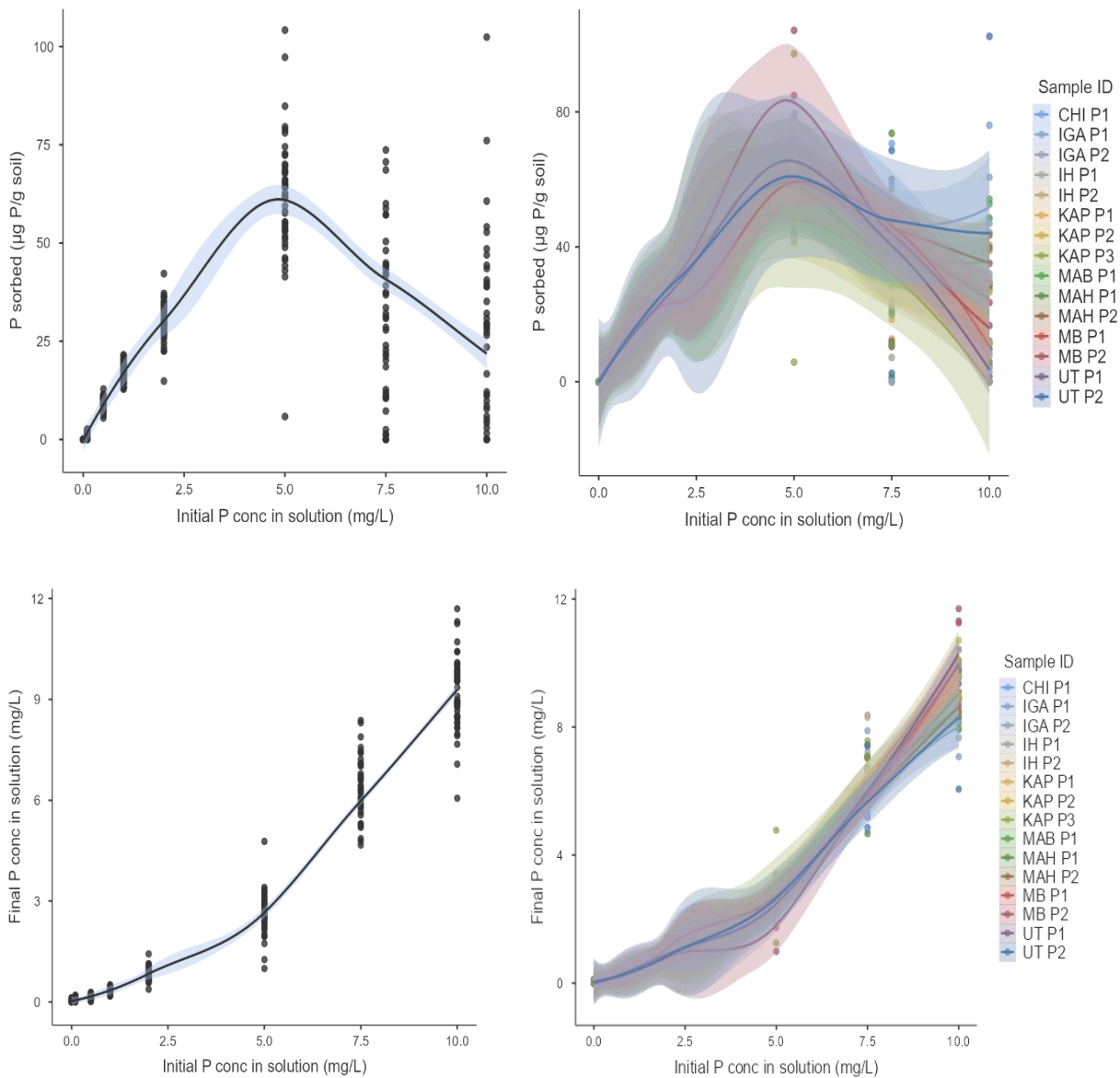
**Table 29: Chemical characteristics of selected soil samples from Usangu agro-ecosystem used in batch sorption-desorption batch experiment (0-30 cm depth, n=15)**

Sample ID	Scheme	C (g/kg)	Al <sub>ox</sub> (mmol/kg)	Fe <sub>ox</sub> (mmol/kg)	PSC (mmol/kg)	P <sub>ox</sub> (mmol/kg)	pH <sub>KCl</sub>
CHI P1	Chimala	13.97	20.12	101.75	71.04	11.41	4.8
IGA P1	Igalako	16.13	23.54	75.33	49.04	10.7	4.6
IGA P2	Igalako	20.15	17.87	111.54	72.11	13.76	5.1
IH P1	Ihahi	13.65	58.21	73.27	62.3	14.48	7.4
IH P2	Ihahi	14.68	32.67	74.22	55.3	13.21	4.8
KAP P1	Kapunga	7.12	19.12	55.18	31.44	3.79	6.1
KAP P2	Kapunga	11.31	12.91	54.33	53.51	12.78	5.3
KAP P3	Kapunga	12.12	22.24	19.56	52.82	14.76	5.3
MB P2	Mabadaga	11.45	18.51	13.34	16.7	3.24	5.4
MAB P1	Mabadaga	28.12	33.44	130.47	76.65	11.42	4.8
MAH P2	Mahongole	15.14	26.43	71.55	49.03	11.95	4.9
MAH P1	Mahongole	16.41	42.33	9.55	24.44	4.72	5.3
MB P1	Mubuyuni	14.93	21.26	39.28	28.43	7.14	4.9
UT P1	Uturo	12.71	18.03	19.25	53.14	10.06	4.9
UT P2	Uturo	14.12	19.62	89.14	63.1	11.49	5.7

**Table 30: The concentration of P in final (F) soil solution (in mg/L) and adsorbed (A) in soil colloids (in mg/kg) during a sorption-desorption batch experiment involving solutions with different initial (I) P concentration (mg/L) among different soil samples (ID) from Usangu agro-ecosystem.**

ID	I	F	A	I	F	A	I	F	A	I	F	A	I	F	A	I	F	A	I	F	A	I	F	A
KAP P1	0	0.02	0.00	0.10	0.07	0.86	0.50	0.12	9.77	1.00	0.34	17.21	2.00	0.76	32.11	5.00	2.80	57.30	7.50	6.12	35.90	10.0	9.37	22.44
KAP P2	0	0.03	0.00	0.10	0.07	0.77	0.50	0.13	9.63	1.00	0.35	16.79	2.00	0.86	29.55	5.00	3.12	48.77	7.50	6.63	22.51	10.0	9.15	22.38
MB P2	0	0.06	0.00	0.10	0.03	1.94	0.50	0.15	9.04	1.00	0.37	16.47	2.00	0.80	31.12	5.00	1.73	85.05	7.50	6.65	22.21	10.0	9.74	21.44
KAP P3	0	0.02	0.00	0.10	0.07	0.75	0.50	0.16	8.94	1.00	0.30	18.10	2.00	0.71	33.65	5.00	3.15	48.17	7.50	6.39	29.40	10.0	10.2	0.00
MB P1	0	0.00	0.00	0.10	0.03	1.71	0.50	0.15	9.21	1.00	0.32	17.63	2.00	1.10	23.51	5.00	2.67	60.48	7.50	5.88	42.07	10.0	9.97	11.57
UT P1	0	0.02	0.00	0.10	0.02	2.18	0.50	0.09	10.72	1.00	0.46	13.95	2.00	0.89	28.81	5.00	2.44	66.59	7.50	6.33	30.53	10.0	10.2	6.08
UT P2	0	0.04	0.00	0.10	0.04	1.62	0.50	0.09	10.72	1.00	0.31	17.89	2.00	0.84	30.08	5.00	2.63	61.71	7.50	6.09	36.74	10.0	8.20	46.87
IH P1	0	0.01	0.00	0.10	0.05	1.35	0.50	0.11	10.24	1.00	0.48	13.61	2.00	0.78	31.82	5.00	2.55	63.62	7.50	6.66	21.93	10.0	9.29	18.41
IH P2	0	0.04	0.00	0.10	0.04	1.48	0.50	0.14	9.37	1.00	0.37	16.30	2.00	0.92	28.05	5.00	2.78	57.68	7.50	7.13	16.55	10.0	9.42	15.03
MAH P2	0	0.03	0.00	0.10	0.04	1.50	0.50	0.13	9.62	1.00	0.38	16.13	2.00	0.78	31.59	5.00	2.70	59.85	7.50	6.11	36.15	10.0	8.55	37.60
CHI P1	0	0.03	0.00	0.10	0.06	1.23	0.50	0.11	10.22	1.00	0.39	15.95	2.00	0.78	31.69	5.00	2.49	65.20	7.50	5.48	52.64	10.0	9.50	12.93
MAH P1	0	0.04	0.00	0.10	0.04	1.49	0.50	0.09	10.60	1.00	0.30	18.17	2.00	0.86	29.71	5.00	2.64	61.32	7.50	6.28	31.64	10.0	8.95	27.25
IGA P1	0	0.06	0.00	0.10	0.02	1.99	0.50	0.18	8.43	1.00	0.42	15.15	2.00	0.79	31.39	5.00	2.51	64.67	7.50	6.48	29.92	10.0	7.85	55.78
IGA P2	0	0.03	0.00	0.10	0.11	0.66	0.50	0.14	9.44	1.00	0.25	19.47	2.00	0.76	32.32	5.00	2.39	67.95	7.50	7.10	17.98	10.0	8.95	30.91
MAB P1	0	0.02	0.00	0.10	0.09	1.07	0.50	0.21	7.44	1.00	0.36	16.65	2.00	0.90	28.63	5.00	2.73	58.94	7.50	6.61	23.20	10.0	8.47	39.65

I-Initial P concentration added (mg/L), F-Final P concentration in solution (mg/L) after 24 hours, A-concentration of P adsorbed in soil colloids (mg/kg) after 24 hours.



**Figure 18: The relationship and correlation of initial P added (mg/L) and the P sorbed (µg/g) in different soil samples studied in batch sorption desorption experiment**

#### **4.1.4. Soil quality and earthworm diversity in Usangu agro-ecosystem as check of impacts of current paddy farming practice**

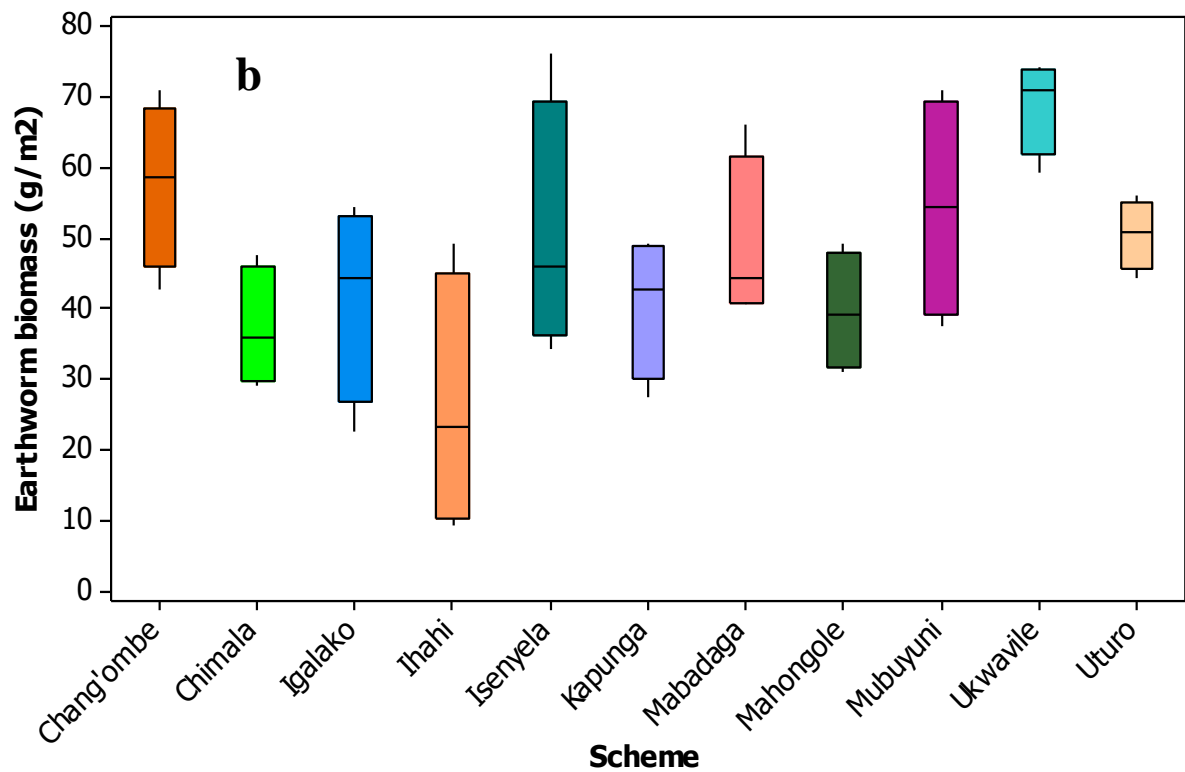
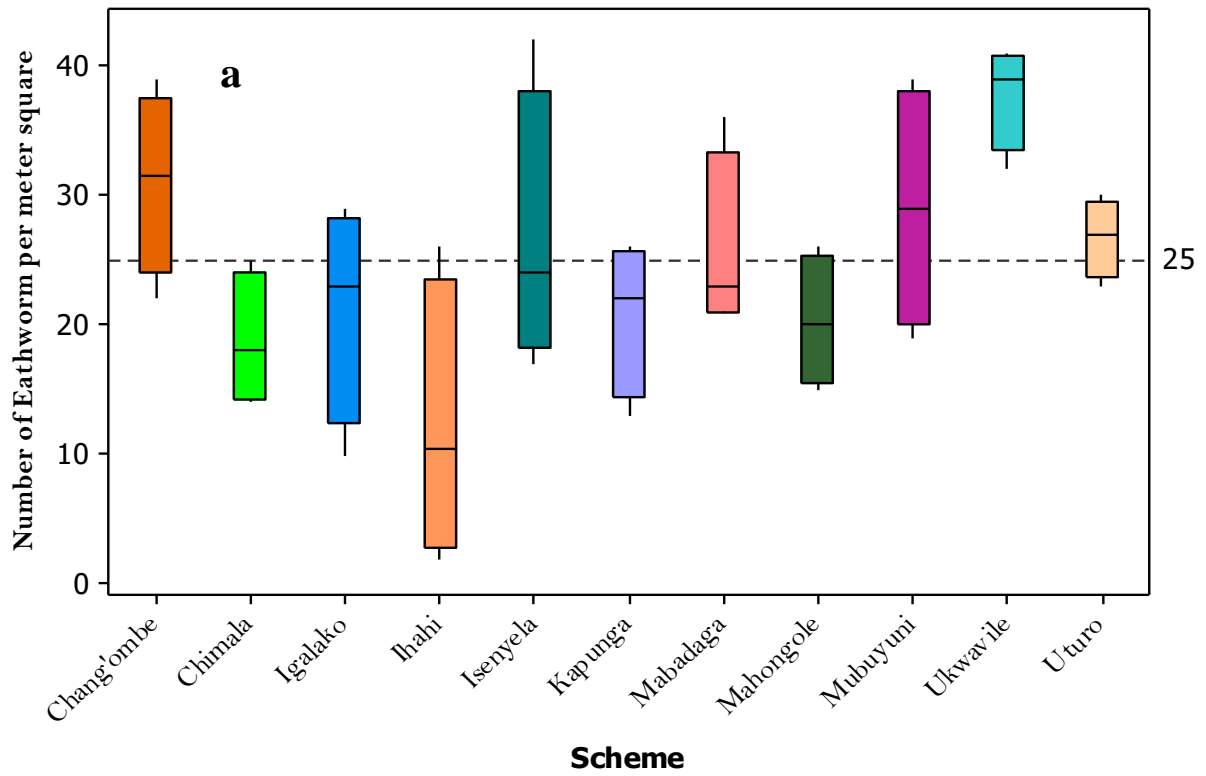
The analysis of soil quality through assessment of soil invertebrates based on earthworms as a key important soil invertebrate in soil nutrient availability and recycling as well as biodegradation of PTEs and plant organic matter. But also, earthworms are sensitive to contamination and land-use practices. Thus assessment of earthworms in different paddy rice irrigation schemes in Usangu agro-ecosystem is important in understanding the influence of the current practices on distribution and biodiversity of earthworms in agricultural soils as an

ecosystem engineer. The results of the assessment of earthworms in different irrigation schemes in Usangu, including species identified, total count per meter square, their biomass such as fresh weight ( $\text{g/m}^2$ ), oven-dry weight ( $\text{g/m}^2$ ), and ash-free weight ( $\text{g/m}^2$ ), the diversity index (H) and species evenness (E) are presented in Table 31, Fig. 19 and 20. Few earthworm species were observed in agricultural soils, about 4 species were observed (Table 31), and most were anecic earthworms, which might be influenced by the deep ploughing and intensive use of agrochemicals in paddy farming and little organic manure or crop residues application as common practice in paddy farming areas.

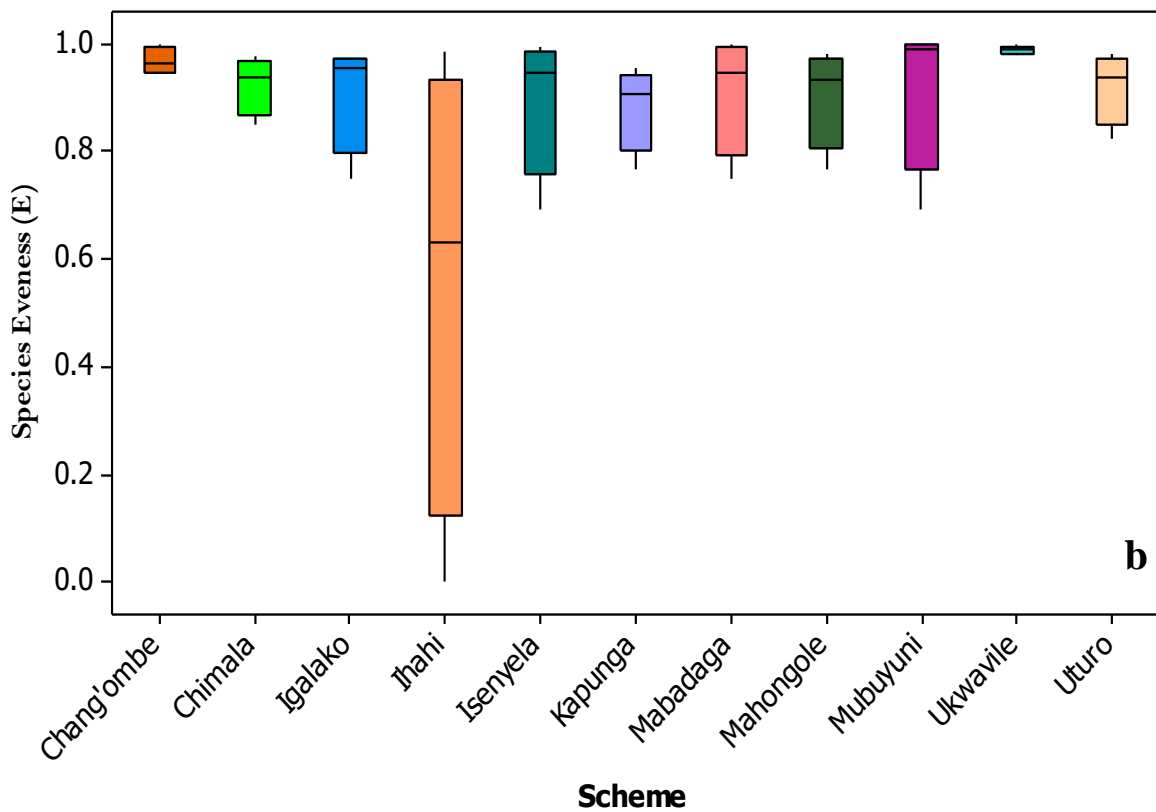
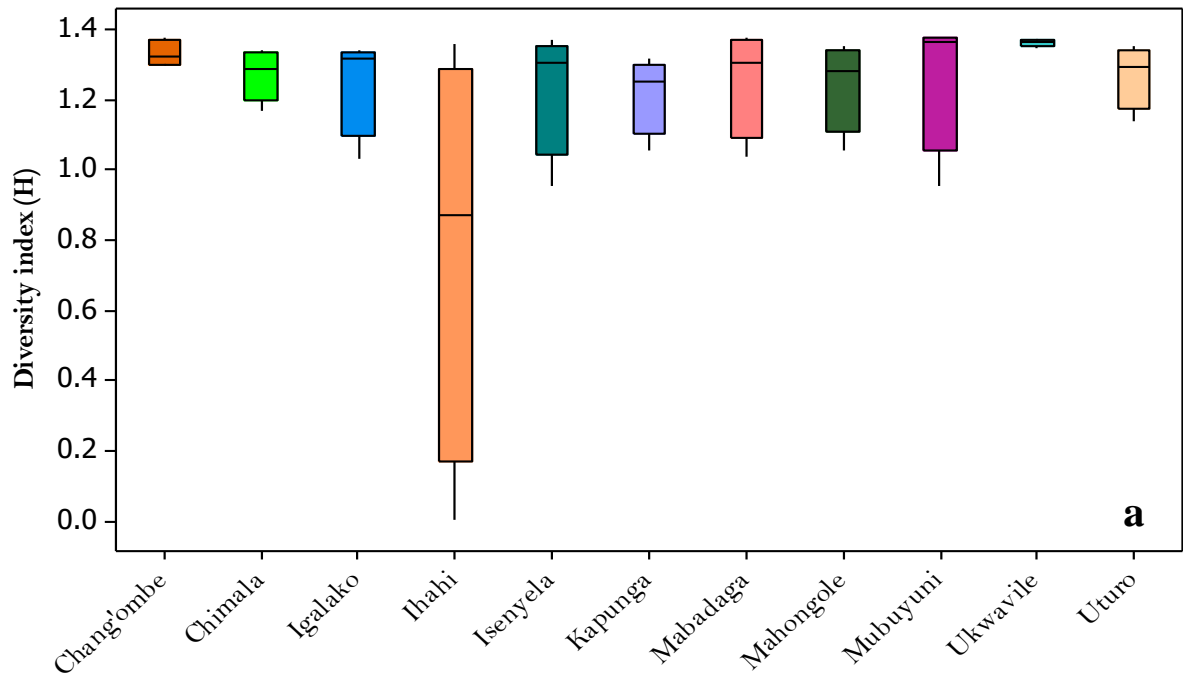
**Table 31: The earthworm mean taxonomic richness and abundance across paddy rice irrigation schemes in the Usangu agro-ecosystem**

Scheme	Mean Earthworm density per m <sup>2</sup>				Earthworm biomass			Diversity index (H)	Specie Evenness (E)	
	<i>A. caliginosa</i>	<i>P. conethrurus</i>	<i>F.spodorachaetus</i>	<i>L. terrestris</i>	Total (count/m <sup>2</sup> )	Fresh weight (g/m <sup>2</sup> )	Oven weight (g/m <sup>2</sup> )			Ash free weight g/m <sup>2</sup> )
Chang'ombe	9.00±2.58	9.25±0.59	6.75±3.86	6.00±2.58	31.00±7.07	164.71±33.73	115.30±23.61	57.65±11.80	1.33±0.04	0.97±0.03
Chimala	5.50±1.29	6.25±3.30	4.50±2.08	2.50±1.29	18.75±5.19	106.29±24.75	74.40±17.32	37.20±8.66	1.27±0.08	0.92±0.05
Igalako	5.75±2.63	4.50±2.38	8.00±2.45	3.00±2.16	21.25±8.38	118.21±39.98	82.75±27.98	41.37±13.99	1.25±0.15	0.91±0.11
Ihahi	3.75±3.86	3.25±2.75	3.75±2.99	1.50±3.00	12.25±10.97	75.29±52.30	52.70±36.61	26.35±18.30	0.78±0.59	0.56±0.43
Isenyela	8.00±2.45	7.75±4.57	6.00±4.90	5.00±2.45	26.75±10.81	144.45±51.57	101.11±36.10	50.56±18.05	1.23±0.19	0.90±0.14
Kapunga	5.50±2.08	8.00±1.83	4.75±3.59	2.50±2.08	20.75±6.02	115.83±28.72	81.08±20.10	40.54±10.05	1.22±0.11	0.89±0.08
Mabadaga	9.75±0.96	3.75±3.86	5.50±1.92	6.75±0.96	25.75±7.09	139.68±33.81	97.77±23.67	48.89±11.83	1.26±0.15	0.91±0.11
Mahongole	7.25±1.50	3.25±2.50	5.50±3.42	4.25±1.50	20.25±5.12	113.44±24.44	79.41±17.11	39.71±8.55	1.24±0.13	0.90±0.10
Mubuyuni	8.25±4.50	7.50±2.38	7.75±1.50	5.50±4.04	29.00±9.52	155.18±45.41	108.62±31.79	54.31±15.89	1.27±0.21	0.92±0.15
Ukwavile	11.75±0.96	8.50±2.65	8.75±2.75	8.75±0.98	37.75±4.03	196.91±19.23	137.84±13.46	68.92±6.73	1.36±0.01	0.99±0.01
Uturo	6.00±1.63	8.25±1.50	9.50±3.79	3.00±1.63	26.75±2.99	144.44±14.24	101.11±9.97	50.56±4.98	1.27±0.09	0.92±0.07
<b>Grand mean</b>	<b>7.32±3.11</b>	<b>6.39±3.28</b>	<b>6.43±3.31</b>	<b>4.43±2.89</b>	<b>24.57±9.33</b>	<b>134.04±44.49</b>	<b>93.83±31.14</b>	<b>46.91±15.57</b>	<b>1.23±0.24</b>	<b>0.89±0.18</b>
<b>P-value</b>	<b>0.003</b>	<b>0.015</b>	<b>0.231</b>	<b>0.002</b>	<b>0.004</b>	<b>0.004</b>	<b>0.004</b>	<b>0.061</b>	<b>0.003</b>	<b>0.015</b>

NB: *Apporectodea caliginosa* (endogeic), *Lumbricus terrestris* (Anecic), *Pontoscolex corentrurus* (endogeic), *Fimoscolex sporadochactus* (Anecic)



**Figure 19: The earthworm abundance (a) and ash free weight earthworm biomass (b) in agricultural soils from different Usangu paddy rice irrigation schemes as of May 2021**



**Figure 20: The earthworm diversity index (a) and earthworm species evenness (b) in agricultural soils from different Usangu paddy rice irrigation schemes as of May 2021**

#### 4.1.5. The PTEs distribution in soils, water, and plants in UA

##### (i) Physico-chemical soil properties of the study area

The overall soil physical and chemical properties of the studied soils are shown in Table 32. The determined soil electric conductivity (EC) were observed to range from 69.7 to 196  $\mu\text{S}/\text{cm}$  where the mean EC value were 102.23  $\mu\text{S}/\text{cm}$ . Higher EC values were found in Ilaji (196.0  $\mu\text{S}/\text{cm}$ ), Igalako (128.0  $\mu\text{S}/\text{cm}$ ), and Uturo (100.9  $\mu\text{S}/\text{cm}$ ). On the other hand, soil pH ranged 6.4 to 7.6 which corresponded to slight acidic to slightly alkaline. The total nitrogen determined in studied soils were 0.02 to 0.17% which found to be lower compared with critical established standard values (Ndakidemi *et al.*, 2008). Organic carbon (OC) determined in studied soils was in the range of 0.37 to 2.37%, whereas most studied soils had less than 2% OC, a commended value in agricultural soils. Soil moisture content (MC) in the soil of the study area ranged from 2.7% to 7.65%.

**Table 32: General soil properties for studied samples from Usangu agro-ecosystem which studied for PTEs distribution in agricultural areas (values as mean  $\pm$  SD based on dry soil wt).**

Scheme	pH	OC (%)	N (%)	EC ( $\mu\text{S}/\text{cm}$ )	MC (%)
Chimala	7.1 $\pm$ 0.1	0.60 $\pm$ 0.21	0.05 $\pm$ 0.01	88.25 $\pm$ 50	3.66 $\pm$ 1.01
Mahangole	6.4 $\pm$ 2.1	1.37 $\pm$ 0.06	0.11 $\pm$ 0.02	91.95 $\pm$ 112	5.78 $\pm$ 0.43
Igalako	6.7 $\pm$ 1.2	0.68 $\pm$ 0.02	0.06 $\pm$ 0.01	128.03 $\pm$ 05	3.54 $\pm$ 0.89
Ilaji	7.2 $\pm$ 0.1	2.37 $\pm$ 0.20	0.17 $\pm$ 0.10	196.00 $\pm$ 18	6.05 $\pm$ 2.32
Mabadaga	7.4 $\pm$ 1.4	1.33 $\pm$ 1.02	0.11 $\pm$ 0.01	78.50 $\pm$ 79	7.65 $\pm$ 3.12
Isenyela	6.6 $\pm$ 1.3	0.75 $\pm$ 0.23	0.06 $\pm$ 0.01	71.40 $\pm$ 25	2.70 $\pm$ 0.64
Ihahi	6.9 $\pm$ 0.1	0.80 $\pm$ 0.01	0.07 $\pm$ 0.01	69.70 $\pm$ 12	5.01 $\pm$ 2.12
Kapunga	7.4 $\pm$ 0.8	0.45 $\pm$ 0.01	0.04 $\pm$ 0.01	89.00 $\pm$ 89	5.07 $\pm$ .21
Mubuyuni	7.5 $\pm$ 0.9	0.37 $\pm$ 0.02	0.03 $\pm$ 0.01	83.00 $\pm$ 140	2.95 $\pm$ 0.04
Uturo	6.7 $\pm$ 1.1	1.99 $\pm$ 0.91	0.16 $\pm$ 0.12	100.90 $\pm$ 175	2.81 $\pm$ 1.21
<b>Overall mean</b>	<b>6.41<math>\pm</math>0.37</b>	<b>1.51<math>\pm</math>0.68</b>	<b>0.11<math>\pm</math>0.05</b>	<b>102.23<math>\pm</math>70.53</b>	<b>4.52<math>\pm</math>1.66</b>

##### (ii) Total PTEs concentrations (*aqua regia* extract)

The concentration of total PTEs (*aqua regia* extract) in studied soil samples among irrigation schemes and land use were found to be significantly ( $P < 0.05$ ) different (Fig. 21 to 23). The total concentration (mean values in mg/kg dry wt) of some PTEs studied were as follows; Zn (18.3), Al (7887.03), Mn (263.14), Cr (1.54), and Co (2.92). Furthermore, the concentration (in  $\mu\text{g}/\text{kg}$  dry wt) of other PTEs studied were Ni (4107), Ag (36.54), Cd (21.49), As (1382), Cu (3342), Antimony (Sb) (27.34), Hg (3.28), Se (2696), Mo (282), and Pb (5661) (Table 33).

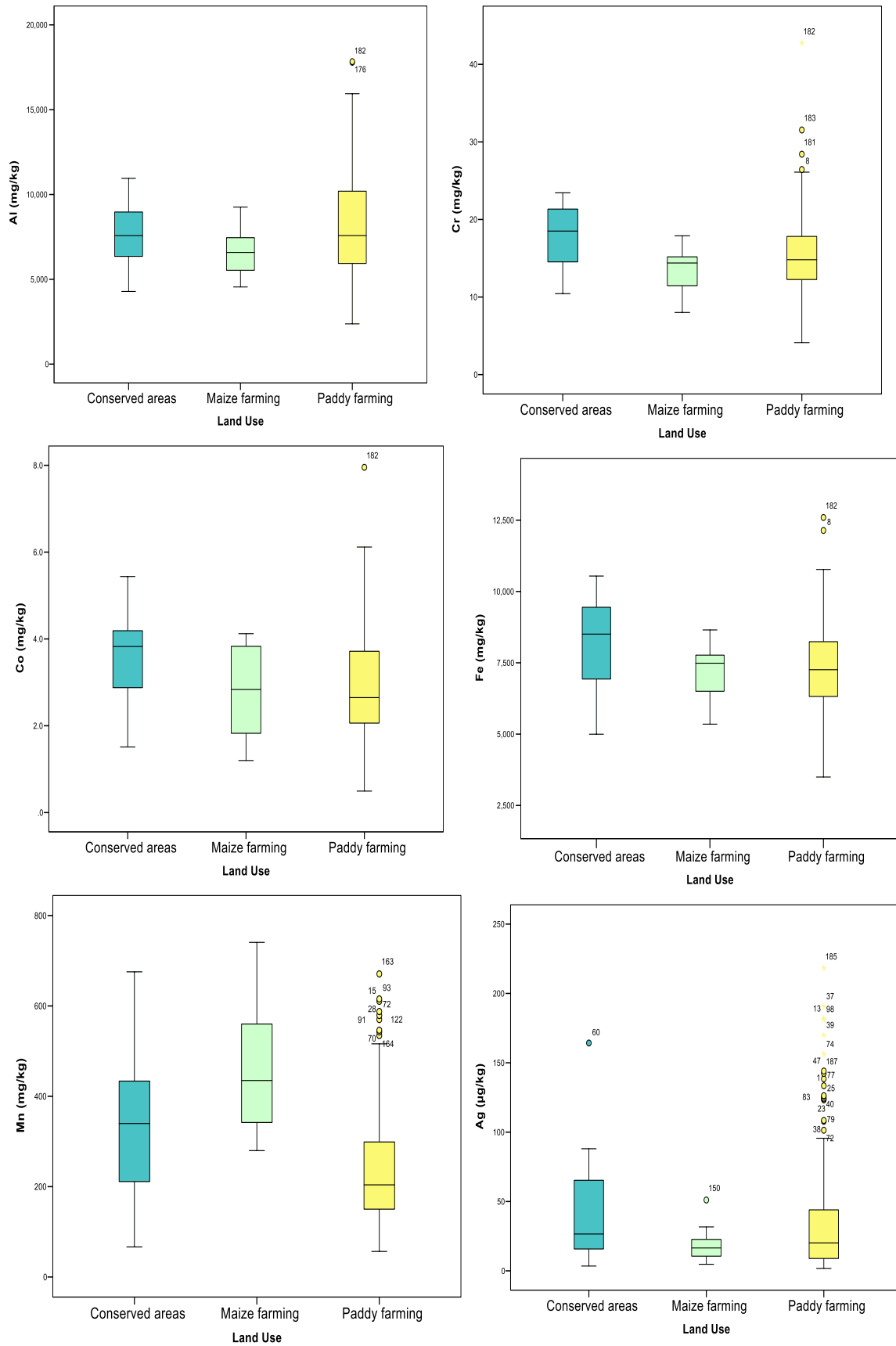
The comparison of total PTEs determined versus Tanzania maximum permissible limit (MAL) in agricultural soils (URT, 2007) found that some PTEs such as Fe, As, Mo, Se, and Ag were above-permitted limits (Table 12). On the other hand, the concentration of Cr, Mn, Cd, Pb, Zn, Hg, and Co were below MAL (Table 12). Where out of 198 soil samples studied, almost 99.48%, 86.53%, 66.32%, and 11.92% of samples had Fe, Se, As, and Hg concentrations above established maximum allowable limits. However, most of the studied soils had total PTEs concentration exceeding the established USEPA limits (Table 12).

Among irrigation scheme groups (Group I and II), concentration (mg/kg dry wt) of total PTEs observed to vary significantly between groups, such as **Al** (Group I=7729.24 and Group II = 8146.79); **Cr** (Group I=1.66 and Group II=1.307); **Co** (Group I= 3.11 and Group II=2.62); **Mn** (Group I=198.25 and Group II=401.32); **Zn** (Group I=17.47 and Group II =19.86). Furthermore, the concentration ( $\mu\text{g/kg}$  dry wt) of other PTEs studied were: **As** (Group I =1303.2 and Group II=1544.11); **Cd** (Group I=18.03 and Group II=29.99); **Cu** (Group I= 4109.06 and Group II =1754.04); and **Pb** (Group I= 5272.27 and Group II= 6655.55). Where generally group I schemes had higher PTEs concentrations than group II (Table 33), however there some PTEs (As, Cd,Cu and Pb) were observed to be significantly higher in group II schemes.

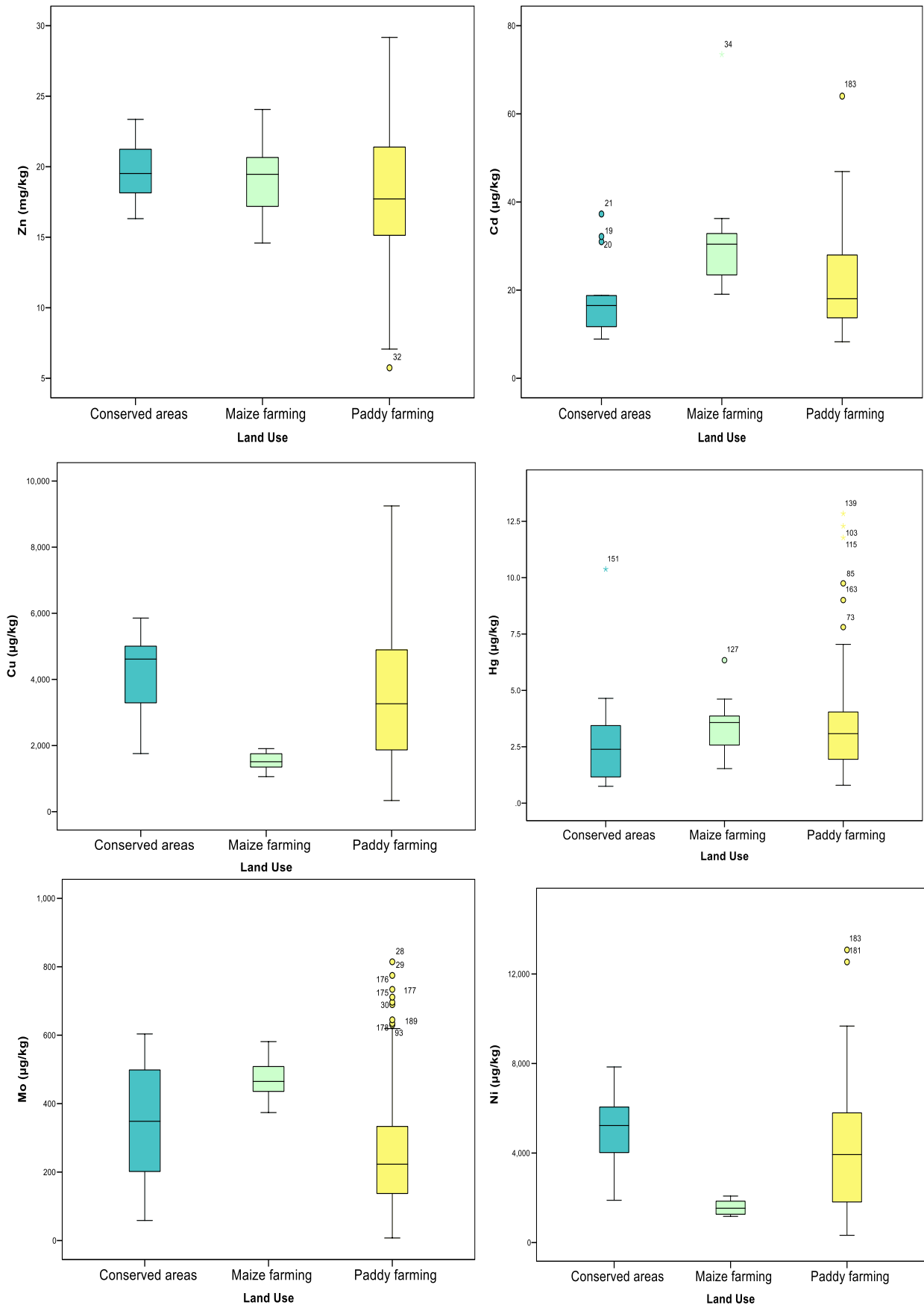
### **(iii) Influence of land use on total PTEs distribution in agro-ecosystem**

The analysis of soil PTEs in maize, paddy, and conservation areas allowed to establish the impact of land use on PTEs distribution across land use. As a result of farming methods and intensifications, the study discovered considerably “higher PTEs concentrations ( $P<0.05$ ) in farmed areas than in conservation areas (Table 35, Fig. 21). Furthermore, soil PTEs were found to be higher in paddy farming (Group II) ( $P<0.05$ ) than in maize farming areas. Generally, PTEs concentrations were statistically substantially lower ( $P<0.05$ ) in conservation areas than in farmed areas (Fig. 21). The concentrations (in mg/kg) of some studied PTEs among land use were; **Pb** in paddy farming (6.578 mg/kg), maize farming (6.324 mg/kg), and conservation area (6.039 mg/kg); **Cr** in paddy (15.31), maize (13.34), and conservation area (11.89); **Al** in paddy (8018.24), maize (6540.72) and conservation areas (7520.81); and **Cd** in paddy (21.06), maize (31.86), and conservation area (17.98). The total PTEs concentration determined among land use scheme classes (Group I and II) demonstrated statistical significance difference between scheme groups, where conservation areas (Group II) had higher PTEs concentration than conservation area group I. While in paddy farming areas (Group II) and maize growing areas

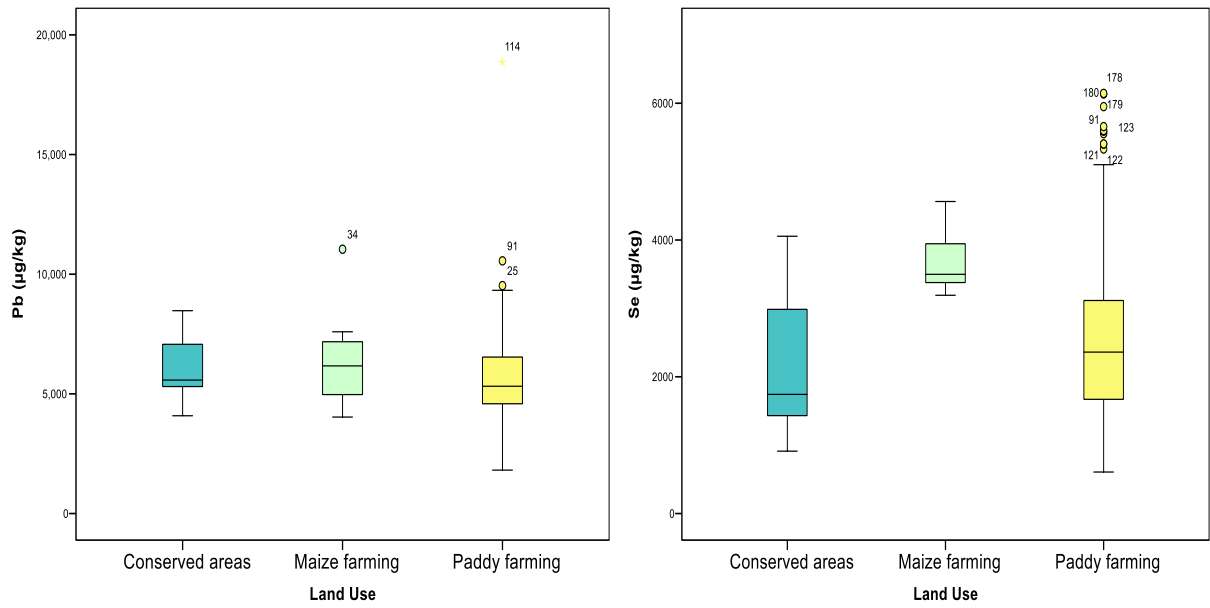
(Group I) were observed to have higher total PTEs concentrations (Table 34). Over the entire land use, Group I had statistically higher Ni, Ag, Cu, As, Cr, and Co, while Group II schemes had a higher Hg, Se, Cd, Pb, and Mo concentration (Table 34). It was observed that some elements (Cr and As) observed to have higher total PTEs concentrations in conservation areas than in maize farming areas. The contamination or pollution hierarchy of studied PTEs were computed by calculating the ratio of total PTEs (AQ) determined with TZ or USEPA maximum permissible limits were computed (Appendix 7 and 8)” (Mng’ong’o *et al.*, 2021). From the computed contamination hierarchy, the ratio of Zn, Mn, Cr, Ag, Mo, Cu, As, Co, Fe, and Pb were higher than USEPA limits. Indicating that AQ:USEPA ratio were significantly higher than 1 ( $P < 0.05$ ). Among 198 studied soil samples Cr (99.48%), Mn (99.34%), Zn (99.42%), As (96.67%), Cu (67.68%), and Pb (96.97%) were observed to exceed USEPA maximum permissible limit for PTEs in agricultural soils. The AQ:TZ ratio as a contamination/pollution hierarchy shown that Mo, Co, Fe, As, and Ag concentrations (Appendix 7 and 8) were above Tanzania's maximum allowable limit (URT, 2007), and the rest of PTEs concentration studied were observed to be below-established maximum permissible limits, however, when compared with USEPA limits most of the studied PTEs were above-established limits.



**Figure 21: Graphical presentation of soil total PTEs distribution among land use in Usangu agro-ecosystem (values as mean ± SD based on soil dry wt)**



**Figure 21: Continue, graphical presentation of soil total PTEs distribution among land use in Usangu agro-ecosystem (values as mean  $\pm$  SD based on soil dry wt)**



**Figure 22: Continue, graphical presentation of soil total PTEs distribution among land use in Usangu agro-ecosystem (values as mean  $\pm$  SD based on soil dry wt)**

**Table 33: The total PTEs concentrations (*aqua regia* extracts) and bioavailable PTEs (M3 extracts) in studied soil samples from Usangu agro-ecosystem (values as mean  $\pm$  SD, n=3)**

Area Classification	Land use	Total Concentration (Aqua regia extracts)	Bioavailable Concentration (Mehlich 3extracts)	Percent bioavailable (% of mean values)	Total Concentration (Aqua regia extracts)	Bioavailable Concentration (Mehlich 3extracts)	Percent bioavailable (% of mean values)
Predominantly agricultural (Group I)		<b>Al (mg/kg dry wt)</b>			<b>Cr (<math>\mu</math>g/kg dry wt)</b>		
	Paddy farming	7817.65 $\pm$ 3165.1	311.02 $\pm$ 164.2	39.8	1643 $\pm$ 5.2	56.35 $\pm$ 37.8	34.3
	Maize farming						
	Conservation forestry	6867.23 $\pm$ 1767	218.37 $\pm$ 76.4	31.8	1846 $\pm$ 4.5	24.19 $\pm$ 23.6	13.1
Mixed settlements and agricultural (Group II)	Paddy farming	8507.17 $\pm$ 2856	259.35 $\pm$ 163.2	30.5	1258 $\pm$ 4.2	8.32 $\pm$ 6.8	66.1
	Maize farming	6854.39 $\pm$ 1532.3	208.31 $\pm$ 163.2	30.4	1395 $\pm$ 2.9	8.32 $\pm$ 6.8	59.6
	Conservation forestry	10135.16 $\pm$ 740.8	195.84 $\pm$ 8.6	19.3	1561 $\pm$ 1.9	ND	ND
Predominantly agricultural (Group I)		<b>Mn (mg/kg dry wt)</b>			<b>Zn (mg/kg dry wt)</b>		
	Paddy farming	190.96 $\pm$ 83.1	114.85 $\pm$ 62.8	60.1	17.30 $\pm$ 3.9	1.89 $\pm$ 0.9	10.9
	Maize farming						
	Conservation forestry	269.4 $\pm$ 119.9	90.55 $\pm$ 63.6	33.6	19.12 $\pm$ 1.9	2.98 $\pm$ 1.9	15.5
Mixed settlements and agricultural (Group II)	Paddy farming	356.45 $\pm$ 152.4	196.21 $\pm$ 91.6	55.1	19.89 $\pm$ 5.3	2.73 $\pm$ 1.2	13.7
	Maize farming	458.51 $\pm$ 116.8	196.95 $\pm$ 34.9	42.9	19.54 $\pm$ 2.8	3.52 $\pm$ 0.3	18.0
	Conservation forestry	631.60 $\pm$ 39.3	298.35 $\pm$ 12.4	47.2	21.40 $\pm$ 1.7	6.34 $\pm$ 0.1	29.6
Predominantly agricultural (Group I)		<b>Ag (<math>\mu</math>g/kg dry wt)</b>			<b>Cd (<math>\mu</math>g/kg dry wt)</b>		
	Paddy farming	31.18 $\pm$ 44.9	14.04 $\pm$ 98.4	45.0	18.43 $\pm$ 8.9	18.37 $\pm$ 7.2	99.6
	Maize farming						
	Conservation forestry	38.58 $\pm$ 44.6	3.35 $\pm$ 2.2	8.7	14.10 $\pm$ 3.5	13.76 $\pm$ 4.9	97.5
Mixed settlements and agricultural (Group II)	Paddy farming	36.82 $\pm$ 44.1	11.41 $\pm$ 15.3	30.9	27.46 $\pm$ 8.3	25.19 $\pm$ 9.1	91.7
	Maize farming	18.81 $\pm$ 10.7	10.18 $\pm$ 16.9	54.1	36.13 $\pm$ 17.8	33.21 $\pm$ 3.1	91.9
	Conservation forestry	66.99 $\pm$ 20.1	7.81 $\pm$ 0.3	11.7	33.48 $\pm$ 3.3	32.19 $\pm$ 0.8	96.1
Predominantly agricultural (Group I)		<b>As (<math>\mu</math>g/kg dry wt)</b>			<b>Mo (<math>\mu</math>g/kg dry wt)</b>		
	Paddy farming	1261.23 $\pm$ 289.0	190.45 $\pm$ 144.1	15.1	223.77 $\pm$ 150.2	0.99 $\pm$ 2.8	0.4
	Maize farming						
	Conservation forestry	1712.54 $\pm$ 574.4	189.22 $\pm$ 151.8	11.1	306.90 $\pm$ 178.6	3.57 $\pm$ 4.9	1.2
Mixed settlements and agricultural (Group II)	Paddy farming	1568.91 $\pm$ 399.2	270.34 $\pm$ 223.2	17.2	354.08 $\pm$ 201.8	2.59 $\pm$ 4.9	0.7
	Maize farming	1456.71 $\pm$ 399.2	179.10 $\pm$ 41.2	12.3	471.96 $\pm$ 68.9	19.48 $\pm$ 19.3	4.1
	Conservation forestry	1568.91 $\pm$ 61.9	161.45 $\pm$ 12.7	10.3	522.66 $\pm$ 42.3	18.40 $\pm$ 1.7	3.5

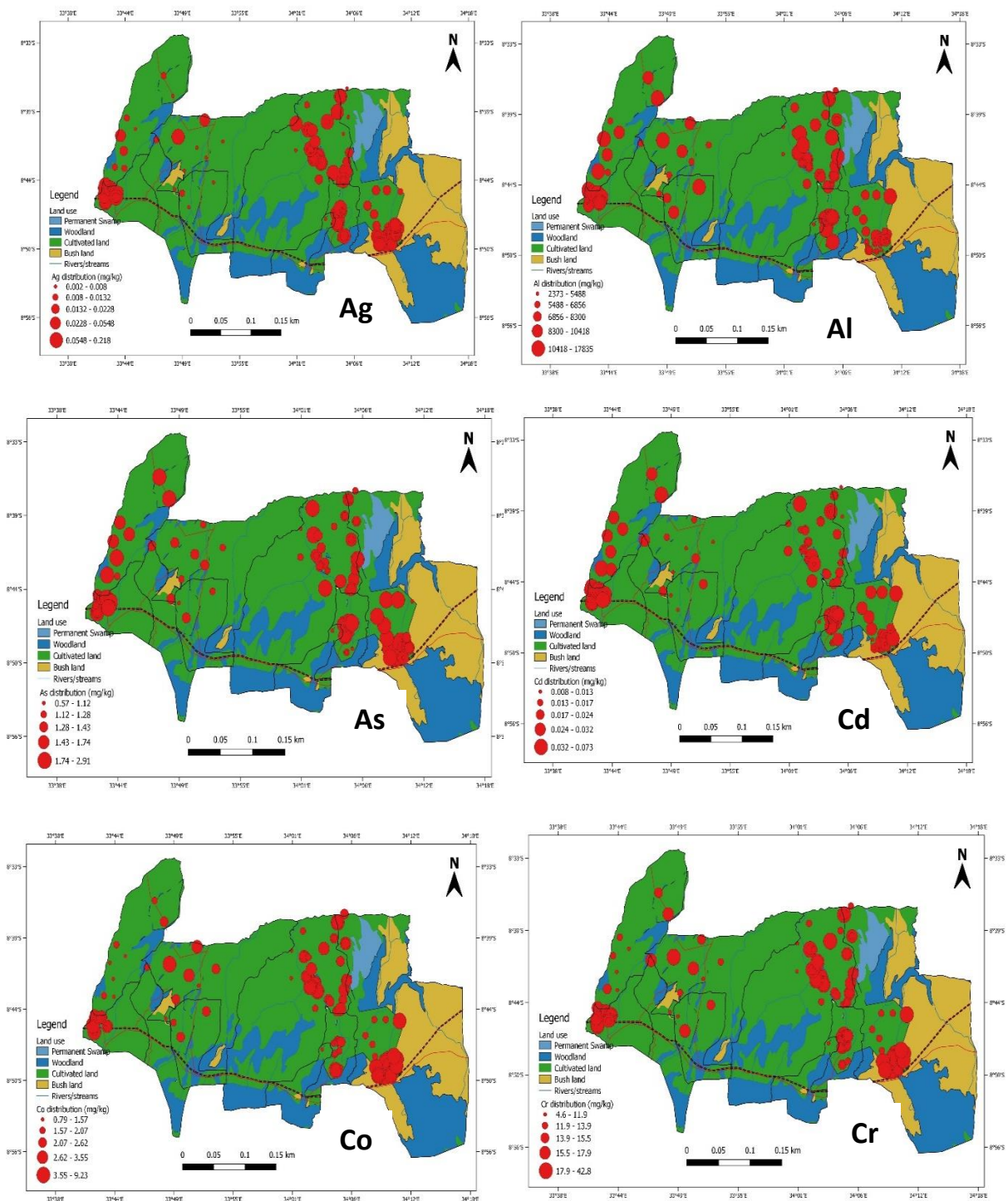
Note; There was only Group II in maize farming areas, ND-not detected

**Table 33: Continue, the total PTEs concentrations (*aqua regia* extracts) and bioavailable PTEs (M3 extracts) in studied soil samples from Usangu agro-ecosystem (values as mean  $\pm$  SD, n=3)**

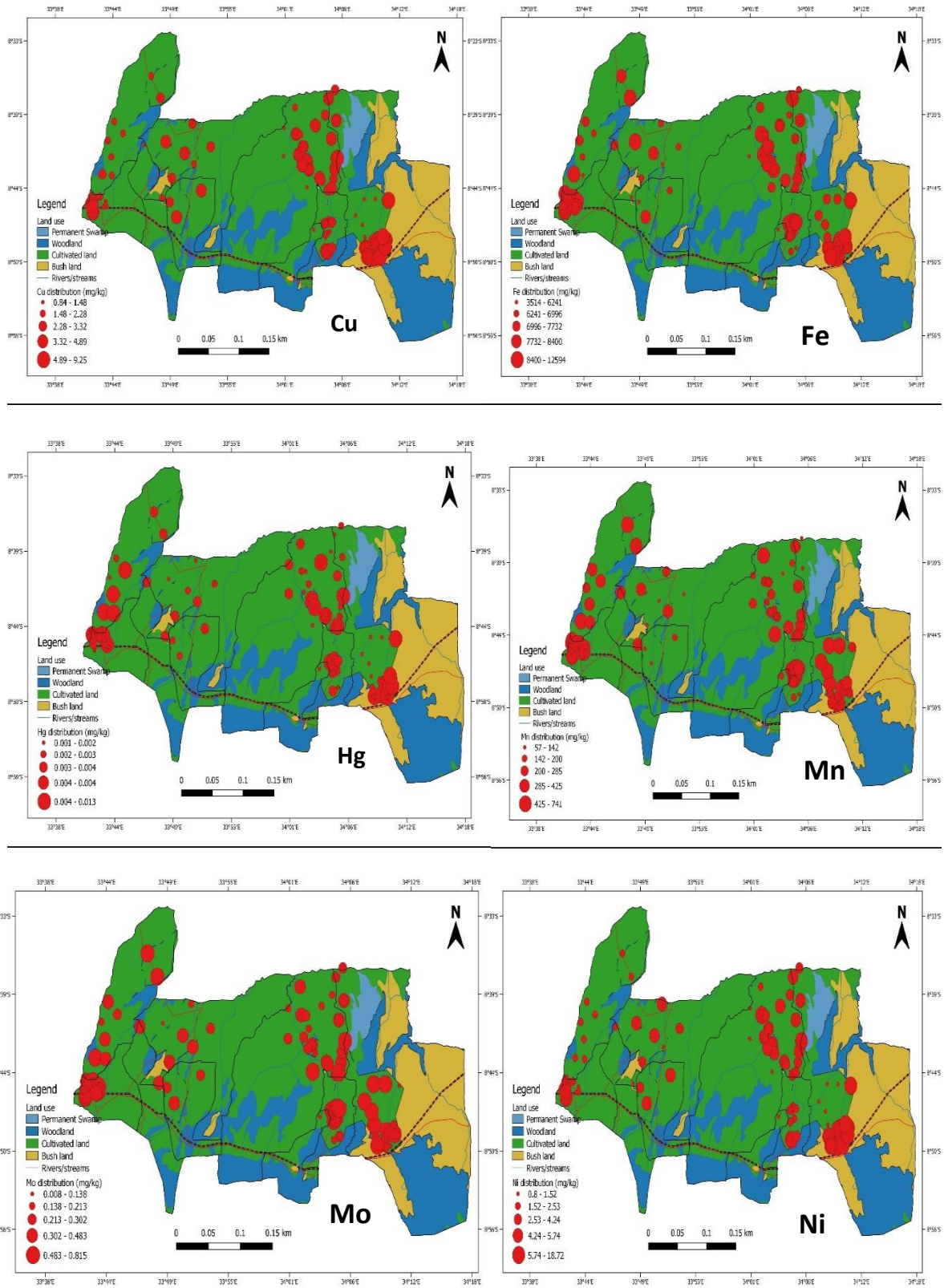
Area Classification	Land use	Total Concentration (Aqua regia extracts)	Bioavailable Concentration (Mehlich 3 extracts)	Percent bioavailable (% of mean values)	Total Concentration (Aqua regia extracts)	Bioavailable Concentration (Mehlich 3 extracts)	Percent bioavailable (% of mean values)
Predominantly agricultural (Group I)		Co ( $\mu\text{g/kg dry wt}$ )			Fe ( $\text{mg/kg dry wt}$ )		
	Paddy farming	3070 $\pm$ 1.2	843.76 $\pm$ 521.2	27.4	7350.79 $\pm$ 1503.0	227.86 $\pm$ 89.1	3.9
	Maize farming						
	Conservation forestry	3410 $\pm$ 1.3	685.81 $\pm$ 553.9	20.1	8182.99 $\pm$ 1878.8	190.11 $\pm$ 82.9	2.3
Mixed settlements and agricultural (Group II)	Paddy farming	2390 $\pm$ 1.0	474.22 $\pm$ 169.2	19.8	7223.08 $\pm$ 1753.9	189.31 $\pm$ 89.1	2.6
	Maize farming	2990 $\pm$ 0.9	532.17 $\pm$ 142.7	17.8	7309.03 $\pm$ 990.0	109.64 $\pm$ 18.4	1.5
	Conservation forestry	4130 $\pm$ 0.4	633.82 $\pm$ 13.0	15.3	8223.37 $\pm$ 864.8	104.58 $\pm$ 8.9	1.2
Predominantly agricultural (Group I)		Pb ( $\mu\text{g/kg dry wt}$ )			Sb ( $\mu\text{g/kg dry wt}$ )		
	Paddy farming	5244.72 $\pm$ 1709.1	1874 $\pm$ 830	35.7	28.77 $\pm$ 24.2	0.89 $\pm$ 0.9	3.1
	Maize farming						
Mixed settlements and agricultural (Group II)	Conservation forestry	5540.78 $\pm$ 896.1	1823 $\pm$ 396	32.9	41.10 $\pm$ 39.9	0.76 $\pm$ 0.7	1.8
	Paddy farming	6391.57 $\pm$ 1945.2	1645 $\pm$ 608	25.7	20.36 $\pm$ 18.3	0.51 $\pm$ 0.4	2.5
	Maize farming	7129.35 $\pm$ 2156.2	1874 $\pm$ 18	26.2	31.29 $\pm$ 11.0	0.34 $\pm$ 0.3	1.1
Predominantly agricultural (Group I)	Conservation forestry	8036.51 $\pm$ 533.5	2023 $\pm$ 2	25.1	30.41 $\pm$ 3.1	0.74 $\pm$ 0.1	2.4
		Cu ( $\mu\text{g/kg dry wt}$ )			Hg ( $\mu\text{g/kg dry wt}$ )		
	Paddy farming	4061.77 $\pm$ 1638.9	2520 $\pm$ 1.4	62.0	3.17 $\pm$ 1.8	0.1 $\pm$ 1.04	3.2
Mixed settlements and agricultural (Group II)	Maize farming						
	Conservation forestry	4570.16 $\pm$ 875.7	2380 $\pm$ 0.9	52.1	2.78 $\pm$ 2.7	ND	ND
	Paddy farming	1830.59 $\pm$ 1287.8	820 $\pm$ 0.4	44.8	3.66 $\pm$ 2.2	0.15 $\pm$ 0.5	4.1
Predominantly agricultural (Group I)	Maize farming	1534.72 $\pm$ 216.1	780 $\pm$ 0.1	50.8	2.86 $\pm$ 1.3	ND	ND
	Conservation forestry	1845.19 $\pm$ 137.9	890 $\pm$ 0.0	48.2	2.81 $\pm$ 0.2	ND	ND
		Se ( $\mu\text{g/kg dry wt}$ )			Ni ( $\mu\text{g/kg dry wt}$ )		
Mixed settlements and agricultural (Group II)	Paddy farming	2101.25 $\pm$ 711.2	1385.81 $\pm$ 962.2	65.9	5160.29 $\pm$ 2568.1	679.16 $\pm$ 763	13.2
	Maize farming						
	Conservation forestry	1801.88 $\pm$ 692.1	1401.99 $\pm$ 939.7	77.8	5497.25 $\pm$ 1092.1	438.28 $\pm$ 288.8	7.9
Predominantly agricultural (Group I)	Paddy farming	4044.26 $\pm$ 1265.0	1743.18 $\pm$ 1514.6	43.1	1957.94 $\pm$ 1540.7	182.22 $\pm$ 258.0	9.3
	Maize farming	3614.15 $\pm$ 426.3	1544.47 $\pm$ 281.8	42.7	1559.06 $\pm$ 294.4	130.18 $\pm$ 50.4	8.4
	Conservation forestry	3940.17 $\pm$ 101.7	1743.18 $\pm$ 98.7	44.2	1965.92 $\pm$ 92.1	102.39 $\pm$ 6.7	5.2

#### **(iv) Spatial total PTEs distribution in Usangu agro-ecosystem**

The spatial PTEs distribution in Usangu agro-ecosystem (Group I and II) were observed to be significantly variable ( $P < 0.001$ ) between groups and irrigation schemes. Schemes in lowland (B and C in Fig. 8) had higher PTEs concentrations ( $P < 0.001$ ), such as Cu, Pb, Fe, Co, Ni, Cr, and Al than their counterparts (Table 35). Furthermore, soil PTEs (Mn, Hg, Zn, Ag, Mo, As, Cd, and Se) concentrations were significantly higher in schemes located closer to urban or peri-urban regions (D and E in Group II in Fig. 8) (Table 34). When the PTEs of irrigation schemes were compared, it was discovered that Group I schemes (Ilaji, Mubuyuni, Mabadaga, Uturo, and Kapunga) had significantly higher Co, Al, Cu, Cr, Ni, Fe, and Pb concentrations, whereas Group II schemes (Ihahi, Chimala, Mahongole, and Igalako) had significantly higher Hg, Mn, As, Zn, Mo, Ag, Cd, and Se (Table 34). All irrigation schemes had PTEs concentrations below permissible ranges, except for As, Ag, Mo, Co, and Fe, which were over the limits according to Tanzania's maximum permissible limits in agricultural soils (Table 12). When overall PTEs concentrations were compared with USEPA limits, it was discovered that all 10 irrigation schemes (Groups I and II) had As, Cr, Mn, Co, Ag, Fe, Zn, Cd, Mo, Cu, and Pb concentrations that were above the limit. PTEs contamination or pollution hierarchy (AQ:TZ and AQ:USEPA) revealed substantial heterogeneity among schemes, with decreasing concentration order of Mabadaga > Chimala > Uturo > Mubuyuni > Mahongole > Ilaji > Kapunga > Igalako > Ihahi > Isenyela (Appendix 7 and 8). The Fig. 22 shows how the concentration and distribution maps of different PTEs varied among studied sites.



**Figure 23: Maps showing soil total PTEs distribution in topsoils (0-30 cm) in Usangu agro-ecosystem**



**Figure 23: Continue: Maps showing soil total PTEs distribution in topsoils in UA**

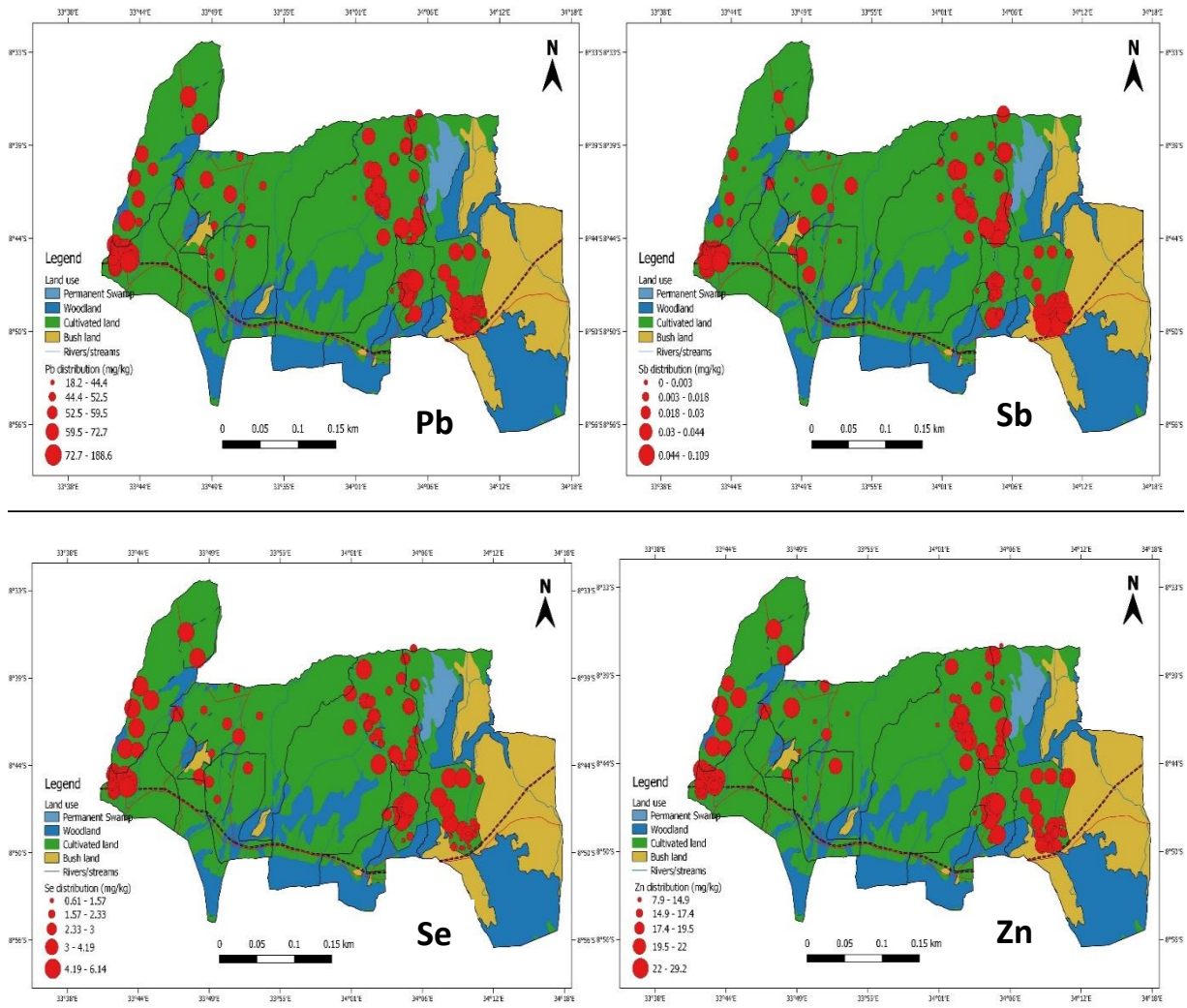


Figure 23: Continue: Maps showing soil total PTEs distribution in topsoils (0-30 cm) in UA

**Table 34: Summary of total PTEs concentrations in dried soil (aqua regia extracts) in Usangu agro-ecosystem, comparing mostly agricultural (Group I) against mixed settlements and agricultural (Group II) landscapes (values as mean  $\pm$  SD, n=3)**

Scheme	Group	Al (mg/kg)	Fe (mg/kg)	Cr (mg/kg)	Co (mg/kg)	Mn (mg/kg)	Zn (mg/kg)	Ni ( $\mu$ g/kg)
Ilaji	I	8400.24 $\pm$ 1187.6	8355.31 $\pm$ 1578.	16.9 $\pm$ 4.8	2.76 $\pm$ 0.9	331.28 $\pm$ 149.8	17.91 $\pm$ 2.3	3209.21 $\pm$ 2405.6
Isenyela	I	3414.05 $\pm$ 931.9	4608.65 $\pm$ 1255.1	5.80 $\pm$ 2.1	1.03 $\pm$ 0.3	317.18 $\pm$ 82.9	7.14 $\pm$ 1.4	380.52 $\pm$ 60.6
Kapunga	I	9152.27 $\pm$ 2927.7	7050.14 $\pm$ 1015.3	14.74 $\pm$ 2.6	2.59 $\pm$ 0.7	178.99 $\pm$ 64.4	18.64 $\pm$ 3.6	4225.70 $\pm$ 1040.3
Mabadaga	I	13793.94 $\pm$ 3490.8	10523.86 $\pm$ 1836.8	34.24 $\pm$ 7.5	6.43 $\pm$ 1.3	236.90 $\pm$ 40.4	20.96 $\pm$ 4.8	14776.84 $\pm$ 3423.8
Mubuyuni	I	5426.67 $\pm$ 1564.4	7581.63 $\pm$ 1725.1	18.25 $\pm$ 4.3	3.66 $\pm$ 1.1	184.99 $\pm$ 102.3	16.09 $\pm$ 2.9	6513.48 $\pm$ 1771.7
Uturo	I	6375.80 $\pm$ 822.1	8297.49 $\pm$ 1603.4	19.55 $\pm$ 5.0	3.87 $\pm$ 1.0	230.08 $\pm$ 66.9	16.84 $\pm$ 3.4	6107.45 $\pm$ 1713.9
Chimala	II	7084.678 $\pm$ 1288.5	9073.32 $\pm$ 774.02	20.59 $\pm$ 2.2	4.11 $\pm$ 0.4	238.69 $\pm$ 22.5	20.62 $\pm$ 2.6	6821.88 $\pm$ 387.1
Igalako	II	7066.779 $\pm$ 1491.8	6808.08 $\pm$ 1422.4	12.79 $\pm$ 4.1	2.98 $\pm$ 0.9	348.42 $\pm$ 147.9	17.73 $\pm$ 4.3	1750.77 $\pm$ 1336.9
Ihahi	II	7354.573 $\pm$ 2747.4	6710.40 $\pm$ 1604.9	11.30 $\pm$ 3.6	1.83 $\pm$ 0.7	376.09 $\pm$ 120.7	19.86 $\pm$ 5.5	1642.05 $\pm$ 564.6
Mahongole	II	10201.698 $\pm$ 2130.4	8204.16 $\pm$ 1017.4	14.72 $\pm$ 2.0	3.29 $\pm$ 0.8	498.37 $\pm$ 164.1	21.29 $\pm$ 3.1	1521.59 $\pm$ 373.2
Scheme	Group	Ag ( $\mu$ g/kg)	Cu ( $\mu$ g/kg)	Se ( $\mu$ g/kg)	Cd ( $\mu$ g/kg)	Hg ( $\mu$ g/kg)	Mo ( $\mu$ g/kg)	Pb ( $\mu$ g/kg)
Ilaji	I	65.43 $\pm$ 53.5	2772.96 $\pm$ 2129.2	2343.27 $\pm$ 791.8	22.51 $\pm$ 8.7	1.08 $\pm$ 1.1	331.28 $\pm$ 245.8	6094.82 $\pm$ 1017.8
Isenyela	I	15.95 $\pm$ 7.3	392.70 $\pm$ 57.9	2038.43 $\pm$ 59.6	17.79 $\pm$ 5.9	2.26 $\pm$ 2.3	392.26 $\pm$ 102.0	4127.71 $\pm$ 402.5
Kapunga	I	42.39 $\pm$ 53.5	3487.32 $\pm$ 869.3	2467.96 $\pm$ 577.8	18.54 $\pm$ 7.9	3.1 $\pm$ 0.8	260.85 $\pm$ 154.2	5469.32 $\pm$ 943.5
Mabadaga	I	9.86 $\pm$ 2.5	7838.97 $\pm$ 1232.3	1955.79 $\pm$ 245.4	35.55 $\pm$ 24.6	4.96 $\pm$ 0.6	47.18 $\pm$ 4.5	3888.99 $\pm$ 835.5
Mubuyuni	I	30.86 $\pm$ 28.5	5007.64 $\pm$ 1238.8	1475.09 $\pm$ 589.5	16.77 $\pm$ 7.7	3.51 $\pm$ 2.4	162.26 $\pm$ 105.8	5152.03 $\pm$ 2656.7
Uturo	I	28.91 $\pm$ 32	5219.88 $\pm$ 1396.36	1695.85 $\pm$ 378.7	13.49 $\pm$ 4.9	3.02 $\pm$ 1.8	233.34 $\pm$ 149.8	4870.34 $\pm$ 1122.0
Chimala	II	52.22 $\pm$ 74.7	5654.76 $\pm$ 5654.8	2143.63 $\pm$ 149.3	16.71 $\pm$ 4.4	4.75 $\pm$ 1.8	262.14 $\pm$ 78.9	5841.09 $\pm$ 709.5
Igalako	II	22.43 $\pm$ 12.6	1712.96 $\pm$ 1713.0	3028.08 $\pm$ 668.7	35.24 $\pm$ 20.4	2.83 $\pm$ 2.1	332.66 $\pm$ 186.8	6840.96 $\pm$ 2792.0
Ihahi	II	31.30 $\pm$ 44.5	1591.12 $\pm$ 1591.1	4418.57 $\pm$ 1132.6	25.83 $\pm$ 7.8	3.65 $\pm$ 2.1	417.30 $\pm$ 188.5	5959.58 $\pm$ 1814.2
Mahongole	II	42.08 $\pm$ 34.0	1459.0 $\pm$ 429.2	4123.35 $\pm$ 613.3	34.07 $\pm$ 3.8	3.31 $\pm$ 1.9	417.34 $\pm$ 168.3	7633.72 $\pm$ 1179.8

#### **(v) Bioavailable PTEs concentrations**

The concentrations of bioavailable PTEs differed significantly between Group I and Group II locations. For example, Co (Group I=0.83 mg/kg and Group II=0.49 mg/kg); Cr (Group I=55.04 µg/kg and Group II=19.21 µg/kg); Cd (Group I=19.22 µg/kg and Group II= 36.82 µg/kg); Cu (Group I =2510 µg/kg and Group II= 810 µg/kg); and Zn (Group I=1.99 mg/kg and Group II= 3.09 mg/kg) (Table 34). The determined bioavailable PTEs concentrations in soil (e.g., Pb and Cd) were in general lower in Group I compared with Group II regions, although Cu concentrations were the opposite. When compared with the results obtained after acid digestion (AQ), the bioavailable PTEs were substantially lower. Among the components investigated, the ratio of M3 to AQ (M3:AQ) was used to determine the per cent of PTE available (%bioavailability) for crop or plant uptake (Table 34, Appendix 10). The distribution of bioavailable PTEs differed greatly between irrigation schemes and land use.

#### **(vi) The bioavailable PTEs distribution in among land use**

The bioavailable PTEs distribution between land use and groups were found to be significantly high in paddy and maize farming areas ( $P<0.05$ ) than in conservation areas (Table 33). Land use group I had a higher Ni, Al, Cr, Fe, Cu, and Co concentration, while group II had higher Mn, Se, Hg, Pb, As, Mo, Zn, Cd, and Ag concentration (Table 33). The concentration of bioavailable PTEs studied among land-use were; As in paddy farming (Group I =190 and Group II= 270 µg/kg), maize farming (Group II =170 µg/kg), and conservation area (Group I= 187 and Group II= 161 µg/kg); Pb in paddy farming (Group I=1.87 and Group II= 1.65 mg/kg), maize farming (Group II= 1.87 mg/kg), and conservation area (Group I= 1.82 and Group II= 2.02 mg/kg); and Cd in paddy farming (Group I= 19 and Group II= 38 µg/kg), maize farming (Group II= 33 µg/kg), and conservation area (Group I= 17 and Group II= 36 µg/kg). The ratio of bioavailable to total PTEs concentration (M3:AQ) in diverse land use differed considerably among PTEs, with greater values determined for Se (43-74%), Ag (11-100%), Mn (33-61.3%), Cd (0-100%), Cu (48-64%), and Pb (25-38%) (Appendix 10).

#### **(vii) Bioavailable PTEs spatial distribution in Usangu agro-ecosystem (UA)**

The distribution of bioavailable PTEs among studied soils from different irrigation schemes in UA were observed to vary significantly different (Appendix 9). Where it was observed that group I schemes had higher PTEs concentration such as Pb (0.64 to 2.74 mg/kg), Al (199 to 346 mg/kg), Co (291 to 1619 µg/kg), Cu (0.3 to 4.2 mg/kg), As (86 to 468 µg/kg), Ag (0.2 to

33.12 µg/kg), and Ni (93.28 to 1770 µg/kg) whilst Group II schemes observed to have higher concentration of Cr (13.5 to 101.5 µg/kg), Mn (118 to 227 mg/kg), Zn (2.5 to 3.4 mg/kg), Hg (0 to 0.35 µg/kg), Cd (18.3 to 39.3 µg/kg), Fe (154 to 324 mg/kg) and Se (0 to 2470.7 µg/kg) (Appendix 9). Based on the M3:AQ ratio, PTEs with higher per cent bioavailability were Mn (Group I= 27 to 81% and Group II= 42 to 67%), As (Group I= 7 to 45% and Group II= 2 to 18%), Cd (Group I= 4 to 100% and Group II= 4 to 100%), and Cu (Group I=12 to 44% and Group II=40 to 54%) (Appendix 10 and 12).

**(viii) Evaluation of PTEs in Usangu agro-ecosystem using pollution and contamination indexes**

The evaluation of PTEs pollution and contamination in Usangu agro-ecosystem were further characterized by different pollution and contamination indexes such as adverse effect index (AEI), geochemical accumulation (Igeo), contamination factor index (CF), pollution load index (PLI), potential ecological risk index (Er), comprehensive risk index (RI), and enrichment factor (EF). The computed indexes were compared with the established limit for interpretation. The indexes were computed based on land uses and irrigation schemes. The results of the computed indexes are presented in Table 35 to 47 below. The interpretation and implication of each computed index are discussed in detail in Section 4.2 under the discussion Subsection.

**Table 35: Adverse effect index (AEI) (based on Tanzanian Soil Quality Guideline (SQGs) values) for different PTEs in different irrigation schemes of Usangu agro-ecosystem**

S/N	Scheme	Cr	Co	Fe	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se
1	Chimala	0.21±0.02	4.11±0.40	1814.66±154.80	0.13±0.01	0.14±0.02	52.22±74.70	1.61±0.10	0.02±0.00	0.03±0.00	0.00	262.14±78.94	0.07±0.00	0.03±0.00	0.11±0.01
2	Igalako	0.11±0.04	2.68±1.00	1249.07±290.64	0.15±0.08	0.11±0.03	24.85±15.79	1.17±0.32	0.03±0.02	0.01±0.01	0.00	243.11±184.00	0.02±0.02	0.03±0.01	0.14±0.03
3	Ihahi	0.11±0.04	1.83±0.71	1342.08±320.98	0.21±0.07	0.13±0.04	31.30±44.50	1.54±0.38	0.03±0.01	0.01±0.00	0.00	417.30±188.50	0.02±0.01	0.03±0.01	0.22±0.06
4	Ilaji	0.17±0.05	2.76±0.94	1671.06±315.60	0.18±0.08	0.12±0.02	65.43±53.48	1.79±0.64	0.02±0.01	0.01±0.01	0.00	331.28±245.77	0.03±0.01	0.03±0.01	0.12±0.04
5	Isenyela	0.06±0.02	1.03±0.33	921.73±251.02	0.18±0.05	0.05±0.01	15.95±7.26	1.06±0.20	0.02±0.01	0.00±0.00	0.00	392.26±101.95	0.00±0.02	0.02±0.00	0.10±0.00
6	Kapunga	0.15±0.03	2.59±0.69	1410.03±203.05	0.10±0.04	0.12±0.02	42.39±53.48	1.28±0.20	0.02±0.01	0.02±0.00	0.00	260.85±154.23	0.04±0.00	0.03±0.00	0.12±0.03
7	Mabadaga	0.34±0.08	6.43±1.34	2104.77±367.35	0.13±0.02	0.14±0.03	9.86±2.49	0.87±0.11	0.04±0.02	0.04±0.01	0.00	47.18±4.50	0.15±0.01	0.02±0.00	0.10±0.01
8	Mahongole	0.15±0.02	3.29±0.81	1640.83±203.47	0.28±0.09	0.14±0.02	42.08±34.01	1.70±0.27	0.03±0.00	0.01±0.00	0.00	417.34±168.28	0.02±0.03	0.04±0.01	0.21±0.03
9	Mubuyuni	0.18±0.04	3.66±1.06	1516.33±345.01	0.10±0.06	0.11±0.02	30.86±28.45	1.26±0.42	0.02±0.01	0.03±0.01	0.00	162.26±105.79	0.07±0.02	0.03±0.01	0.07±0.03
10	Uturo	0.20±0.05	3.87±0.95	1659.50±320.69	0.13±0.04	0.11±0.02	28.90±31.95	1.45±0.37	0.01±0.00	0.03±0.01	0.00	233.33±149.81	0.06±0.02	0.02±0.01	0.08±0.02

**Table 36: Adverse effect index (AEI) based on Tanzanian Soil Quality Guideline values for different PTEs in different land use in Usangu agro-ecosystem**

<b>PTEs</b>	<b>Land Use</b>	<b>Mean</b>	<b>SD</b>	<b>Minimum</b>	<b>Maximum</b>
Cr	Conservation Area	0.18	0.04	0.10	0.23
	Maize farming	0.13	0.03	0.08	0.18
	Paddy farming	0.15	0.05	0.04	0.43
Co	Conservation Area	3.56	1.15	1.51	5.44
	Maize farming	2.78	1.06	1.20	4.12
	Paddy farming	2.87	1.16	0.50	7.95
Fe	Conservation Area	1638.21	339.45	999.24	2108.37
	Maize farming	1427.49	202.69	1069.80	1730.33
	Paddy farming	1462.73	315.31	698.95	2518.80
Mn	Conservation Area	0.19	0.10	0.04	0.38
	Maize farming	0.26	0.08	0.16	0.41
	Paddy farming	0.13	0.07	0.03	0.37
Zn	Conservation Area	0.13	0.01	0.11	0.16
	Maize farming	0.13	0.02	0.10	0.16
	Paddy farming	0.12	0.03	0.04	0.19
Ag	Conservation Area	44.86	42.28	3.46	164.26
	Maize farming	18.81	12.94	4.74	51.08
	Paddy farming	37.07	44.24	1.78	218.39
As	Conservation Area	1.70	0.51	1.02	2.91
	Maize farming	1.40	0.19	1.11	1.74
	Paddy farming	1.35	0.35	0.57	2.30
Cd	Conservation Area	0.02	0.01	0.01	0.04
	Maize farming	0.03	0.01	0.02	0.07
	Paddy farming	0.02	0.01	0.01	0.06
Cu	Conservation Area	0.02	0.01	0.01	0.03
	Maize farming	0.01	0.00	0.01	0.01
	Paddy farming	0.02	0.01	0.00	0.05
Hg	Conservation Area	0.00	0.00	0.00	0.01
	Maize farming	0.00	0.00	0.00	0.00
	Paddy farming	0.00	0.00	0.00	0.01
Mo	Conservation Area	350.05	182.49	58.53	603.60
	Maize farming	474.45	63.01	373.93	581.31
	Paddy farming	261.68	176.51	7.55	814.55
Ni	Conservation Area	0.05	0.02	0.02	0.08
	Maize farming	0.02	0.00	0.01	0.02
	Paddy farming	0.04	0.03	0.00	0.19
Pb	Conservation Area	0.03	0.01	0.02	0.04
	Maize farming	0.03	0.01	0.02	0.06
	Paddy farming	0.03	0.01	0.01	0.09
Se	Conservation Area	0.11	0.05	0.05	0.20
	Maize farming	0.18	0.02	0.16	0.23
	Paddy farming	0.13	0.06	0.03	0.31

**Table 37: Geochemical accumulation ( $I_{geo}$ ) index for different PTEs in soils from Usangu agro-ecosystem**

Scheme	Al	Cr	Co	Fe	Mg	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se
Chimala	0.07	0.10	0.21	0.07	0.10	0.06	0.10	0.11	0.04	0.10	0.16	-0.25	-0.52	0.14	0.16	0.16
Igalako	0.07	0.11	0.25	0.07	0.11	0.06	0.11	0.11	0.04	0.09	0.23	-0.22	-0.54	0.20	0.16	0.16
Ihahi	0.07	0.11	0.30	0.07	0.12	0.06	0.10	0.11	0.04	0.09	0.22	-0.23	-0.97	0.20	0.16	0.14
Ilaji	0.06	0.11	0.24	0.07	0.11	0.06	0.10	0.09	0.04	0.10	0.21	-0.16	-0.74	0.19	0.16	0.16
Isenyela	0.07	0.13	0.38	0.07	0.13	0.06	0.12	0.11	0.04	0.10	0.39	-0.20	-0.76	0.34	0.17	0.16
Kapunga	0.06	0.11	0.25	0.07	0.11	0.06	0.10	0.11	0.04	0.10	0.18	-0.21	-0.58	0.16	0.16	0.16
Mabadaga	0.06	0.09	0.19	0.07	0.09	0.06	0.10	0.12	0.04	0.09	0.15	-0.26	-0.23	0.12	0.17	0.17
Mahongole	0.06	0.11	0.23	0.07	0.12	0.06	0.10	0.10	0.04	0.09	0.23	-0.22	-0.88	0.20	0.15	0.14
Mubuyuni	0.07	0.10	0.22	0.07	0.11	0.06	0.11	0.11	0.04	0.10	0.16	-0.22	-0.39	0.14	0.17	0.18
Uturo	0.07	0.10	0.22	0.07	0.11	0.06	0.10	0.11	0.04	0.10	0.16	-0.21	-0.52	0.15	0.17	0.17

**Table 38: Geochemical accumulation ( $I_{geo}$ ) index for different PTEs in agricultural soils among land use in Usangu agro-ecosystem**

Land Use	Al	Cr	Co	Fe	Mg	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se	
Mean	Conservation Area	0.07	0.10	0.23	0.07	0.11	0.06	0.10	0.10	0.04	0.10	0.17	-0.20	-0.74	0.16	0.16	0.17
	Maize farming	0.07	0.11	0.25	0.07	0.12	0.06	0.10	0.11	0.04	0.09	0.22	-0.22	-0.95	0.20	0.16	0.14
	Paddy farming	0.07	0.11	0.25	0.07	0.11	0.06	0.10	0.11	0.04	0.10	0.19	-0.22	-0.60	0.17	0.16	0.16
Minimum	Conservation Area	0.06	0.10	0.19	0.07	0.10	0.06	0.10	0.08	0.04	0.09	0.15	-0.35	-1.37	0.14	0.15	0.14
	Maize farming	0.06	0.10	0.21	0.07	0.11	0.06	0.10	0.09	0.04	0.08	0.21	-0.28	-1.28	0.18	0.14	0.14
	Paddy farming	0.06	0.09	0.17	0.07	0.09	0.06	0.10	0.08	0.04	0.08	0.14	-0.39	-3.38	0.12	0.12	0.13
Maximum	Conservation Area	0.07	0.11	0.30	0.07	0.12	0.07	0.10	0.15	0.04	0.11	0.21	-0.15	-0.24	0.19	0.17	0.20
	Maize farming	<b>0.07</b>	<b>0.12</b>	<b>0.33</b>	<b>0.07</b>	<b>0.13</b>	<b>0.06</b>	<b>0.11</b>	<b>0.14</b>	<b>0.04</b>	<b>0.10</b>	<b>0.25</b>	<b>-0.18</b>	<b>-0.70</b>	<b>0.22</b>	<b>0.17</b>	<b>0.15</b>
	Paddy farming	<b>0.07</b>	<b>0.13</b>	<b>0.58</b>	<b>0.08</b>	<b>0.14</b>	<b>0.07</b>	<b>0.12</b>	<b>0.17</b>	<b>0.05</b>	<b>0.11</b>	<b>0.43</b>	<b>-0.15</b>	<b>-0.14</b>	<b>0.36</b>	<b>0.21</b>	<b>0.23</b>

**Table 39: Contamination factor (CF) index for different PTEs in agricultural soils from Usangu agro-ecosystem**

Scheme	Al	Cr	Co	Fe	Mg	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se
Chimala	881.18	0.31	0.41	2592.38	665.28	0.40	0.30	1.04	0.13	0.17	0.25	0.24	0.17	0.22	0.28	0.04
Igalako	844.55	0.17	0.27	1784.38	424.66	0.46	0.24	0.50	0.09	0.29	0.08	0.18	0.16	0.06	0.27	0.05
Ilaji	1044.81	0.25	0.28	2387.23	419.46	0.55	0.26	1.31	0.14	0.23	0.12	0.05	0.22	0.10	0.29	0.05
Mahongole	1268.87	0.22	0.33	2344.05	301.17	0.83	0.31	0.84	0.13	0.34	0.06	0.17	0.28	0.05	0.36	0.08
Isenyela	424.63	0.09	0.10	1316.76	177.43	0.53	0.10	0.32	0.08	0.18	0.02	0.11	0.26	0.01	0.20	0.04
Mabadaga	1715.66	0.51	0.64	3006.82	1559.74	0.39	0.31	0.20	0.07	0.36	0.35	0.25	0.03	0.48	0.19	0.04
Kapunga	1138.34	0.22	0.26	2014.32	393.72	0.30	0.27	0.85	0.10	0.19	0.15	0.16	0.17	0.14	0.26	0.05
Mubuyuni	674.96	0.27	0.37	2166.18	603.29	0.31	0.24	0.62	0.10	0.17	0.22	0.18	0.11	0.21	0.25	0.03
Ihahi	908.01	0.17	0.18	1921.66	277.25	0.63	0.29	0.64	0.12	0.26	0.07	0.18	0.28	0.05	0.28	0.09
Uturo	793.01	0.29	0.39	2370.71	630.11	0.38	0.25	0.58	0.11	0.13	0.23	0.15	0.16	0.20	0.23	0.03

**Table 40: Contamination factor (CF) index for different PTEs in agricultural soils among land use in Usangu agro-ecosystem**

Land Use	Al	Cr	Co	Fe	Mg	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se
Conservation Area	935.42	0.27	0.36	2340.31	553.81	0.57	0.29	0.90	0.13	0.18	0.18	0.14	0.23	0.15	0.29	0.04
Maize farming	813.52	0.20	0.28	2039.27	289.80	0.77	0.28	0.38	0.11	0.32	0.07	0.17	0.32	0.05	0.30	0.07
Paddy farming	996.60	0.23	0.29	2091.44	446.84	0.40	0.26	0.75	0.11	0.21	0.15	0.17	0.17	0.14	0.27	0.05

**Table 41: Pollution load index (PLI) for different PTEs in agricultural soils among land use in Usangu agro-ecosystem**

Land Use	Mean	Median	SD	Minimum	Maximum
Conservation Area	1.01	0.98	0.17	0.74	1.27
Maize farming	0.91	0.90	0.16	0.62	1.14
Paddy farming	0.88	0.88	0.18	0.40	1.30

**Table 42: Pollution load index (PLI) for different PTEs in agricultural soils from Usangu agro-ecosystem**

Scheme	Mean	Median	SD	Minimum	Maximum
Chimala	1.12	1.16	0.17	0.93	1.26
Igalako	0.79	0.82	0.20	0.58	1.14
Ihahi	0.86	0.89	0.21	0.40	1.30
Ilaji	0.90	0.86	0.20	0.70	1.26
Isenyela	0.48	0.45	0.08	0.43	0.57
Kapunga	0.88	0.86	0.13	0.68	1.25
Mabadaga	1.16	1.20	0.14	1.01	1.28
Mahongole	1.02	1.04	0.14	0.80	1.27
Mubuyuni	0.87	0.90	0.16	0.44	1.08
Uturo	0.93	0.94	0.14	0.67	1.18

**Table 43: Potential ecological risk index (Er) for different PTEs in agricultural soils from Usangu agro-ecosystem**

Scheme	Al	Cr	Co	Fe	Mg	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se
Chimala	35247.15	0.61	16.45	103695.06	26611.19	0.40	0.30	41.77	1.26	5.01	1.26	9.49	6.99	1.10	1.39	1.71
Igalako	33781.83	0.33	10.71	71375.17	16986.37	0.46	0.24	19.88	0.92	8.69	0.40	7.18	6.48	0.31	1.33	2.18
Ihahi	36320.35	0.34	7.36	76866.43	11089.93	0.63	0.29	25.69	1.21	7.70	0.35	7.20	11.29	0.26	1.42	3.53
Ilaji	41792.22	0.50	11.02	95489.21	16778.53	0.55	0.26	52.34	1.41	6.75	0.62	2.16	8.83	0.52	1.45	1.87
Isenyela	16985.31	0.17	4.14	52670.23	7097.02	0.53	0.10	12.76	0.84	5.34	0.09	4.52	10.46	0.06	0.98	1.63
Kapunga	45533.67	0.44	10.36	80572.98	15748.66	0.30	0.27	33.91	1.01	5.56	0.77	6.20	6.96	0.68	1.30	1.97
Mabadaga	68626.56	1.02	25.73	120272.66	62389.52	0.39	0.31	7.89	0.68	10.66	1.74	9.93	1.26	2.38	0.93	1.56
Mahongole	50754.72	0.44	13.16	93761.88	12046.91	0.83	0.31	33.66	1.34	10.22	0.32	6.61	11.13	0.25	1.82	3.30
Mubuyuni	26998.34	0.54	14.65	86647.16	24131.48	0.31	0.24	24.69	0.99	5.03	1.11	7.01	4.33	1.05	1.23	1.18
Uturo	31720.38	0.58	15.47	94828.44	25204.40	0.38	0.25	23.12	1.14	4.05	1.16	6.04	6.22	0.99	1.16	1.36

**Table 44: Potential ecological risk index (Er) for different PTEs in agricultural soils among land use in Usangu agro-ecosystem**

Land Use	Al	Cr	Co	Fe	Mg	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se
Conservation Area	37416.98	0.53	14.22	93612.23	22152.44	0.57	0.29	35.89	1.34	5.39	0.89	5.56	9.33	0.77	1.44	1.78
Maize farming	32540.93	0.40	11.11	81570.75	11591.98	0.77	0.28	15.05	1.11	9.56	0.34	6.86	12.65	0.25	1.51	2.94
Paddy farming	39864.20	0.46	11.51	83657.68	17873.51	0.40	0.26	29.80	1.06	6.30	0.76	6.61	6.98	0.68	1.33	2.12

**Table 45: Comprehensive ecological risk index (RI) for different PTEs in agricultural soils from Usangu agro-ecosystem**

Element	Al	Cr	Co	Fe	Mg	Mn	Zn	Ag	As	Cd	Cu	Hg	Mo	Ni	Pb	Se
<b>Mean RI</b>	7489474.3	87.5	2234.2	16102892.5	3402645.6	83.6	50.9	5606.1	207.6	1228.9	142.2	1249.3	1436.8	126.9	257.4	410.3

**Table 46: Enrichment factor (EF) computed for multiple PTEs studied in agricultural soils of different land uses in Usangu agro-ecosystem**

PTEs	Land Use	Mean	SD	Minimum	Maximum
Al	Conservation Area	0.42761	0.17358	0.17687	0.73484
	Maize farming	0.39651	0.03900	0.34077	0.46587
	Paddy farming	0.48087	0.17659	0.19730	1.11775
Cr	Conservation Area	0.00342	0.00123	0.00139	0.00526
	Maize farming	0.00496	0.00084	0.00395	0.00655
	Paddy farming	0.00306	0.00211	0.00061	0.01174
Co	Conservation Area	0.00015	0.00003	0.00010	0.00018
	Maize farming	0.00013	0.00004	0.00008	0.00018
	Paddy farming	0.00014	0.00004	0.00005	0.00025
Mg	Conservation Area	0.23588	0.05037	0.13441	0.29180
	Maize farming	0.14161	0.00847	0.12916	0.15105
	Paddy farming	0.21488	0.09168	0.08236	0.52099
Mn	Conservation Area	0.00024	0.00012	0.00006	0.00048
	Maize farming	0.00037	0.00009	0.00028	0.00055
	Paddy farming	0.00019	0.00010	0.00006	0.00064
Zn	Conservation Area	0.00013	0.00003	0.00009	0.00018
	Maize farming	0.00014	0.00001	0.00013	0.00016
	Paddy farming	0.00013	0.00003	0.00007	0.00021
Ag	Conservation Area	0.00000	0.00000	0.00000	0.00000
	Maize farming	0.00000	0.00000	0.00000	0.00000
	Paddy farming	0.00000	0.00000	0.00000	0.00000
As	Conservation Area	0.00006	0.00001	0.00004	0.00008
	Maize farming	0.00005	0.00000	0.00005	0.00006
	Paddy farming	0.00005	0.00001	0.00002	0.00008
Cd	Conservation Area	0.00008	0.00004	0.00003	0.00014
	Maize farming	0.00015	0.00005	0.00011	0.00030
	Paddy farming	0.00010	0.00005	0.00003	0.00025
Cu	Conservation Area	0.00077	0.00023	0.00034	0.00098
	Maize farming	0.00033	0.00004	0.00028	0.00038
	Paddy farming	0.00073	0.00037	0.00012	0.00170
Hg	Conservation Area	0.00007	0.00009	0.00002	0.00036
	Maize farming	0.00009	0.00003	0.00004	0.00014
	Paddy farming	0.00008	0.00005	0.00002	0.00038
Mo	Conservation Area	0.00010	0.00005	0.00002	0.00016
	Maize farming	0.00016	0.00003	0.00012	0.00021
	Paddy farming	0.00008	0.00006	0.00000	0.00028
Ni	Conservation Area	0.00007	0.00002	0.00003	0.00009
	Maize farming	0.00002	0.00000	0.00002	0.00003
	Paddy farming	0.00007	0.00004	0.00001	0.00018
Pb	Conservation Area	0.00013	0.00003	0.00009	0.00018
	Maize farming	0.00015	0.00003	0.00012	0.00021
	Paddy farming	0.00013	0.00004	0.00005	0.00044

**Table 47: Enrichment factor (EF) computed for multiple PTEs studied in agricultural soils of different irrigation schemes from Usangu agro-ecosystem**

<b>Scheme</b>	<b>Al</b>	<b>Cr</b>	<b>Co</b>	<b>Mg</b>	<b>Mn</b>	<b>Zn</b>	<b>Ag</b>	<b>As</b>	<b>Cd</b>	<b>Cu</b>	<b>Hg</b>	<b>Mo</b>	<b>Ni</b>	<b>Pb</b>
Chimala	0.3382	0.0019	0.0002	0.2565	0.0002	0.0001	0.0000	0.0001	0.0001	0.0010	0.0001	0.0001	0.0001	0.0001
Igalako	0.4884	0.0052	0.0002	0.2495	0.0003	0.0001	0.0000	0.0001	0.0002	0.0004	0.0001	0.0001	0.0000	0.0001
Ihahi	0.4575	0.0045	0.0001	0.1444	0.0003	0.0002	0.0000	0.0001	0.0001	0.0004	0.0001	0.0002	0.0000	0.0002
Ilaji	0.4491	0.0024	0.0001	0.1760	0.0002	0.0001	0.0000	0.0001	0.0001	0.0005	0.0000	0.0001	0.0000	0.0001
Isenyela	0.3226	0.0030	0.0001	0.1378	0.0004	0.0001	0.0000	0.0001	0.0002	0.0001	0.0001	0.0002	0.0000	0.0002
Kapunga	0.5749	0.0029	0.0001	0.1963	0.0002	0.0001	0.0000	0.0001	0.0001	0.0008	0.0001	0.0001	0.0001	0.0001
Mabadaga	0.5658	0.0107	0.0002	0.5191	0.0001	0.0001	0.0000	0.0000	0.0001	0.0012	0.0001	0.0000	0.0002	0.0001
Mahongole	0.5406	0.0032	0.0001	0.1296	0.0004	0.0001	0.0000	0.0001	0.0002	0.0003	0.0001	0.0001	0.0000	0.0002
Mubuyuni	0.3202	0.0023	0.0002	0.2870	0.0001	0.0001	0.0000	0.0001	0.0001	0.0011	0.0001	0.0001	0.0001	0.0001
Uturo	0.3433	0.0026	0.0002	0.2776	0.0002	0.0001	0.0000	0.0001	0.0001	0.0010	0.0001	0.0001	0.0001	0.0001

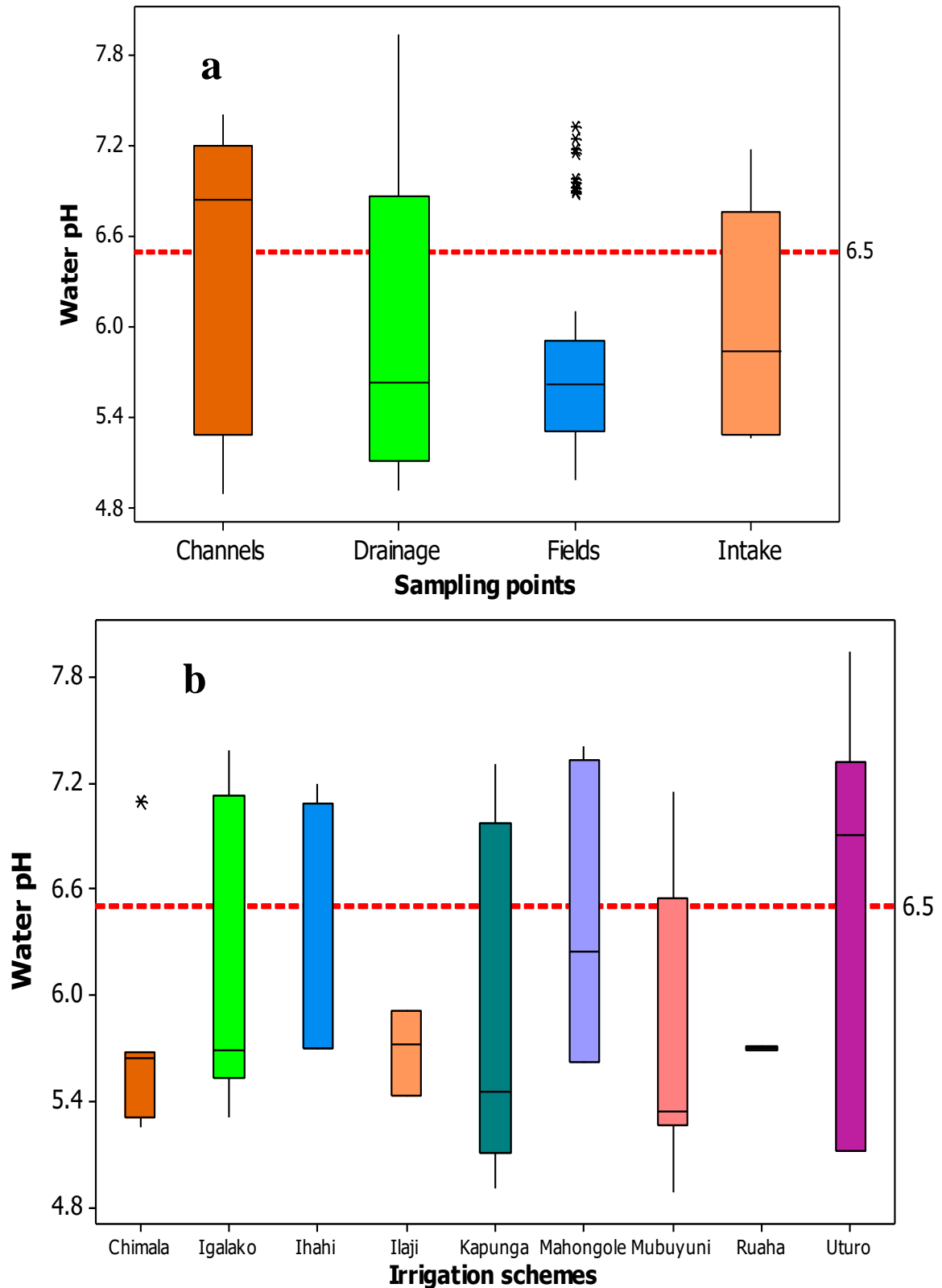
#### **4.1.6. Water quality and surface water P concentrations in paddy farming areas and possible risk relationship of P loss to water body eutrophication**

##### **(i) Water pH**

The general pattern of water pH at the Usangu basin ranged from 4.9 to 7.8, with a mean of 5.5 (Table 48). The study found that water samples collected from intakes had higher water pH near the acceptable range (slightly acidic) while water samples from channels, fields, and drainages were acidic (low pH) (Fig. 24, Table 48 and 50). The water pH comparison among schemes in the area evidenced that some schemes had low pH, such as Uturo and Kapunga. In addition, Kapunga and Mubuyuni were observed to have very variable pH (Fig. 24, Table 49). The study observed some water pH values determined to be below the minimum acceptable limit (6.5 to 8.4) (FAO, 2008).

##### **(ii) Electrical Conductivity (EC)**

The EC determines the capacity of water to conduct electric current carried by various ions in a solution like chloride, bicarbonate, sodium, sulphate, nitrate, calcium, carbonates, and magnesium (Marchese *et al.*, 2008; Visconti & Paz, 2013). The EC estimates the total dissolved salts or total salinity in irrigation water. This implies that a lower EC indicates a low concentration of dissolved salts and *vice versa*; water with electrical conductivity (EC) less than 3000  $\mu\text{S}/\text{cm}$  is considered free from salinity and better for crop production (FAO, 1985). The EC of studied water samples from Usangu agro-ecosystem were found to range from 30 to 2130  $\mu\text{S}/\text{cm}$  with a mean value of 202  $\mu\text{S}/\text{cm}$  (Table 48). Therefore, irrigation water in Usangu agro-ecosystem is classified to have low salinity risks and less water use restrictions. The comparison of the EC values of water in Usangu at different sampling points (i.e., intakes, channels, fields, and drainages) showed that water in drainages and paddy fields had higher EC than those water in intakes and channels (Table 50). The spatial EC distribution in Usangu agro-ecosystem were found to be higher in some schemes such as Mahongole, Kapunga, Ihahi, Ilaji, and Igalako which had more than 208  $\mu\text{S}/\text{cm}$  (Table 49).



**Figure 24: Water pH in different sampling points (a) and irrigation schemes (b) in Usangu agro-ecosystem, the red dotted line is FAO minimum recommended pH (6.5) in irrigation water**

**Table 48: The generalized summary of chemical characteristics of water samples collected from Usangu agro-ecosystem**

	pH	EC ( $\mu\text{S/cm}$ )	Cl <sup>-</sup> (mg/L)	Ca <sup>2+</sup> (mg/L)	HCO <sub>3</sub> <sup>-</sup> (mg/L)	CO <sub>3</sub> <sup>2-</sup> (mg/L)	Mg <sup>2+</sup> (mg/L)
Mean	5.92	201.52	8803	26.61	125.81	13.77	109.93
Median	5.43	134.20	10455	10.6	137.25	11.00	106.02
SD	0.38	362.95	4361	4.65	43.68	9.23	46.53
Minimum	4.89	10.60	0.00	3.86	42.70	1.10	2.94
Maximum	7.94	2130.30	13644	280.00	189.10	48.40	428.69
	NH <sub>4</sub> -N (mg/L)	NO <sub>3</sub> -N (mg/L)	Total N (mg/L)	Total P (mg/L)	Cu (mg/L)	Zn (mg/L)	Fe (mg/L)
Mean	20.41	12.76	33.24	0.31	0.19	0.65	9.64
Median	21.56	13.16	34.72	0.08	0.25	0.66	4.88
SD	10.43	6.51	16.94	0.35	0.05	0.14	22.73
Minimum	8.68	0.08	8.94	0.01	0.003	0.06	0.02
Maximum	70.03	33.88	101.67	1.65	0.31	1.23	105.37

**Table 49: The summary of water chemical composition among schemes in Usangu agro-ecosystem (Value as means $\pm$ sd)**

Scheme	pH	EC ( $\mu\text{S/cm}$ )	Cl <sup>-</sup> (mg/L)	HCO <sub>3</sub> <sup>-</sup> (mg/L)	CO <sub>3</sub> <sup>2-</sup> (mg/L)	NH <sub>4</sub> -N (mg/L)	NO <sub>3</sub> -N (mg/L)
Chimala	5.61 $\pm$ 0.19	115.58 $\pm$ 31.73	12049.60 $\pm$ 970.56	110.34 $\pm$ 54.68	17.05 $\pm$ 9.66	20.30 $\pm$ 3.40	14.49 $\pm$ 1.61
Igalako	6.25 $\pm$ 0.17	222.50 $\pm$ 18.62	9096.27 $\pm$ 4495.96	152.50 $\pm$ 16.50	9.53 $\pm$ 4.40	25.60 $\pm$ 3.52	22.03 $\pm$ 9.75
Ihahi	6.25 $\pm$ 0.00	233.20 $\pm$ 0.01	7442.40 $\pm$ 0.01	189.10 $\pm$ 0.01	48.40 $\pm$ 0.23	10.64 $\pm$ 1.12	12.61 $\pm$ 0.00
Ilaji	5.69 $\pm$ 0.10	208.15 $\pm$ 0.05	8594.20 $\pm$ 4949.88	160.13 $\pm$ 25.06	18.70 $\pm$ 3.60	24.36 $\pm$ 12.58	15.82 $\pm$ 2.61
Kapunga	5.88 $\pm$ 0.32	354.12 $\pm$ 642.36	7816.49 $\pm$ 4820.19	126.07 $\pm$ 39.37	13.44 $\pm$ 5.83	22.30 $\pm$ 5.72	13.14 $\pm$ 4.54
Mahongole	6.41 $\pm$ 0.00	274.10 $\pm$ 0.00	10277.60 $\pm$ 0.01	163.17 $\pm$ 0.01	5.50 $\pm$ 1.12	28.01 $\pm$ 1.23	29.12 $\pm$ 0.00
Mubuyuni	5.72 $\pm$ 0.25	51.52 $\pm$ 31.44	6822.20 $\pm$ 4516.61	100.40 $\pm$ 42.07	11.55 $\pm$ 7.84	29.73 $\pm$ 18.79	15.45 $\pm$ 8.26
Ruaha	5.70 $\pm$ 0.01	92.45 $\pm$ 42.01	12315.40 $\pm$ 1455.85	111.33 $\pm$ 8.35	8.80 $\pm$ 2.41	25.62 $\pm$ 5.98	13.16 $\pm$ 2.76
Uturo	6.47 $\pm$ 0.01	37.40 $\pm$ 0.00	12049.60 $\pm$ 0.00	57.95 $\pm$ 0.01	8.80 $\pm$ 1.10	17.08 $\pm$ 1.23	12.32 $\pm$ 0.00
Scheme	Total N (mg/L)	Total P (mg/L)	Cu (mg/L)	Zn (mg/L)	Fe (mg/L)	Ca <sup>2+</sup> (mg/L)	Mg <sup>2+</sup> (mg/L)
Chimala	34.79 $\pm$ 5.01	0.16 $\pm$ 0.10	0.26 $\pm$ 0.03	0.62 $\pm$ 0.04	8.17 $\pm$ 0.66	10.42 $\pm$ 1.55	104.22 $\pm$ 14.45
Igalako	47.63 $\pm$ 13.27	0.37 $\pm$ 0.23	0.21 $\pm$ 0.08	0.72 $\pm$ 0.07	10.57 $\pm$ 1.36	17.43 $\pm$ 3.93	174.30 $\pm$ 38.28
Ihahi	23.25 $\pm$ 0.01	1.65 $\pm$ 0.00	0.19 $\pm$ 0.01	0.69 $\pm$ 0.01	86.34 $\pm$ 0.01	11.57 $\pm$ 0.01	115.66 $\pm$ 0.01
Ilaji	40.18 $\pm$ 15.19	0.12 $\pm$ 0.10	0.19 $\pm$ 0.01	0.61 $\pm$ 0.05	4.39 $\pm$ 0.53	16.14 $\pm$ 1.85	161.45 $\pm$ 18.48
Kapunga	35.44 $\pm$ 10.26	0.22 $\pm$ 0.34	0.24 $\pm$ 0.04	0.63 $\pm$ 0.07	7.10 $\pm$ 8.09	9.24 $\pm$ 1.94	92.37 $\pm$ 19.44
Mahongole	57.13 $\pm$ 0.12	0.11 $\pm$ 0.00	0.31 $\pm$ 0.01	0.82 $\pm$ 0.01	105.37 $\pm$ 0.01	20.24 $\pm$ 0.02	202.41 $\pm$ 2.31
Mubuyuni	45.18 $\pm$ 27.05	0.11 $\pm$ 0.16	0.25 $\pm$ 0.05	0.64 $\pm$ 0.01	6.02 $\pm$ 3.10	8.67 $\pm$ 3.88	86.75 $\pm$ 38.81
Ruaha	38.78 $\pm$ 8.74	0.03 $\pm$ 0.01	0.28 $\pm$ 0.01	0.68 $\pm$ 0.02	3.41 $\pm$ 0.01	8.07 $\pm$ 1.45	80.72 $\pm$ 14.52
Uturo	29.40 $\pm$ 2.10	0.02 $\pm$ 0.00	0.31 $\pm$ 0.01	0.66 $\pm$ 0.00	3.90 $\pm$ 0.01	6.75 $\pm$ 0.01	67.47 $\pm$ 6.23

**Table 50: The general summary of water chemical composition in different water sampling points in Usangu irrigation schemes**

	Sampling Point	pH	Ec (µS/cm)	CL (mg/L)	HCO <sub>3</sub> <sup>-</sup> (mg/L)	CO <sub>3</sub> <sup>2-</sup> (mg/L)	NH <sub>4</sub> -N (mg/L)	NO <sub>3</sub> -N (mg/L)
Mean	Channels	6.37	50.45	7796.80	125.05	8.80	19.88	9.39
	Drainage	5.84	409.14	7442.40	144.11	18.98	25.26	15.68
	Fields	5.74	149.36	9442.23	128.14	13.59	23.39	17.28
	Intake	5.97	61.36	10206.72	78.39	9.02	24.57	11.28
SD	Channels	0.14	22.84	2135.24	26.73	2.41	0.00	0.47
	Drainage	0.30	666.74	4993.42	40.16	12.61	17.24	7.24
	Fields	0.27	76.01	4607.25	42.94	6.99	6.21	6.55
	Intake	0.28	38.61	1567.57	26.63	8.16	4.00	2.13
Minimum	Channels	4.89	29.60	5847.60	100.65	6.60	19.88	8.96
	Drainage	4.91	67.10	0.00	61.00	8.80	10.64	8.96
	Fields	4.98	37.40	0.00	57.95	5.50	12.88	11.48
	Intake	5.26	29.80	7619.60	42.70	1.10	20.16	8.42
Maximum	Channels	7.41	71.30	9746.00	149.45	11.00	19.99	9.82
	Drainage	7.94	2130.30	12935.60	189.10	48.40	70.03	31.64
	Fields	7.33	274.10	13644.40	183.00	30.80	35.84	33.88
	Intake	7.18	130.80	11695.20	118.95	24.20	29.41	14.01
	Sampling Point	Total N (mg/L)	Total P (mg/L)	Cu (mg/L)	Zn (mg/L)	Fe (mg/L)	Ca <sup>2+</sup> (mg/L)	Mg <sup>2+</sup> (mg/L)
Mean	Channels	29.27	0.07	0.22	0.55	3.90	5.06	50.60
	Drainage	40.94	0.44	0.23	0.79	18.23	10.27	102.71
	Fields	40.67	0.20	0.24	0.62	14.11	12.79	127.88
	Intake	35.85	0.02	0.27	0.34	4.88	8.96	89.64
SD	Channels	0.47	0.06	0.03	0.05	0.00	1.32	13.20
	Drainage	23.64	0.58	0.04	0.06	27.58	1.43	14.30
	Fields	12.76	0.18	0.06	0.13	25.77	5.03	50.35
	Intake	5.92	0.01	0.03	0.23	2.55	2.60	25.99
Minimum	Channels	28.84	0.01	0.19	0.50	3.90	3.86	38.55
	Drainage	23.25	0.02	0.19	0.53	2.93	8.19	81.93
	Fields	28.84	0.02	0.12	0.35	3.41	6.75	67.47
	Intake	29.98	0.01	0.25	0.63	3.41	6.02	60.24
Maximum	Channels	29.70	0.13	0.25	0.60	3.98	6.27	62.65
	Drainage	101.67	1.65	0.31	0.72	86.34	12.53	125.30
	Fields	64.12	0.54	0.31	1.23	105.37	22.65	226.51
	Intake	43.42	0.04	0.31	0.54	9.76	13.49	134.94

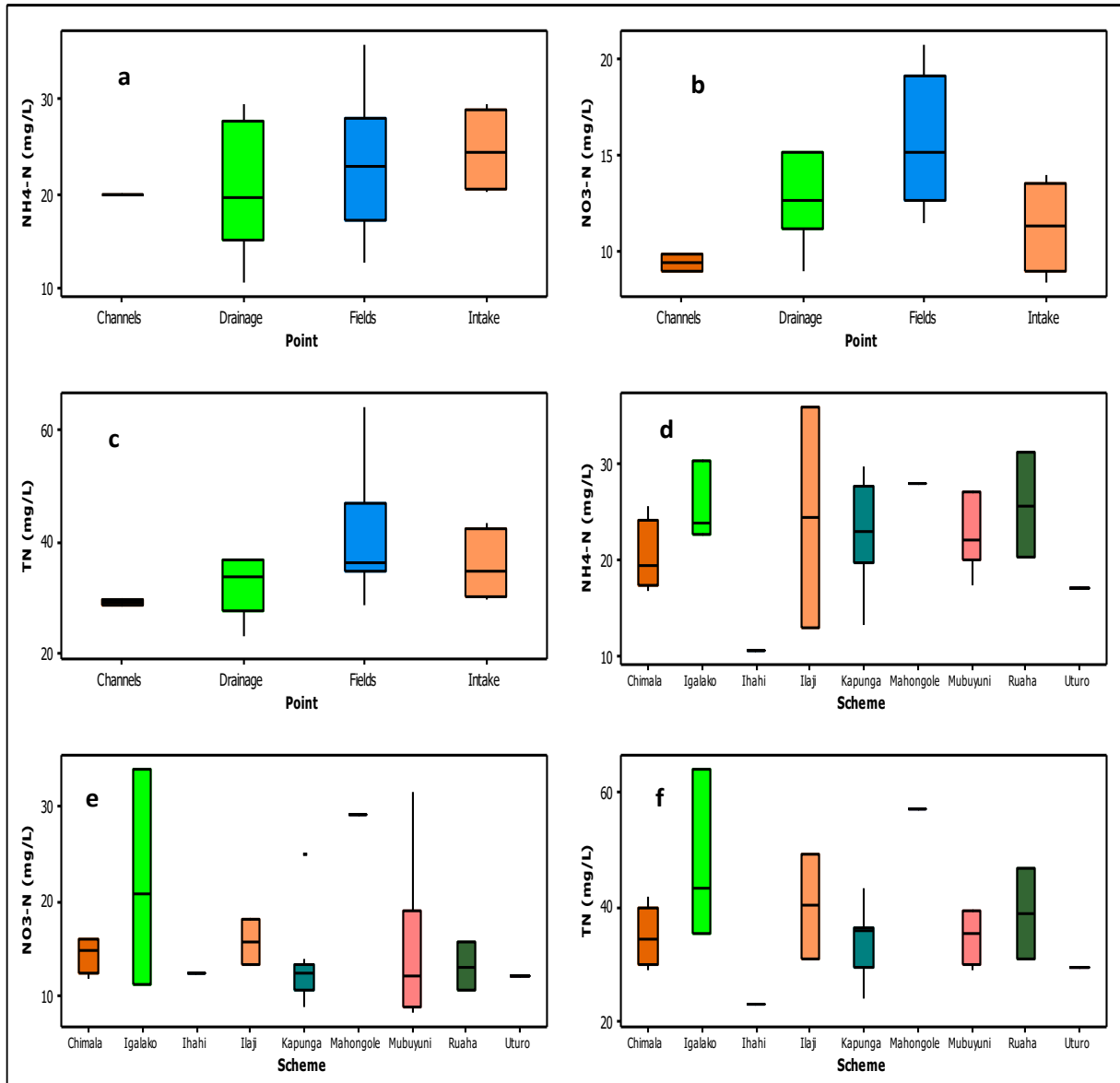
**(iii) Carbonates (CO<sub>3</sub><sup>2-</sup>) and Bicarbonate (HCO<sub>3</sub><sup>-</sup>)**

Carbonates and bicarbonate (CO<sub>3</sub><sup>2-</sup> and HCO<sub>3</sub><sup>-</sup>) in irrigation water are important as it has a close association with calcium (Ca<sup>2+</sup>) and magnesium (Mg<sup>2+</sup>). Both Ca and Mg react with bicarbonate in water and soil to form CaCO<sub>3</sub> or MgCO<sub>3</sub>, respectively (Fipps, 2003; Guo *et al.*, 2021; Marchese *et al.*, 2008; van der Lee *et al.*, 2021). The precipitation of either Ca or Mg in water as carbonate salts increase sodium proportions, thus increasing the sodium hazard rating (Ali *et al.*, 2016; FAO, 1985). The acceptable range of HCO<sub>3</sub><sup>-</sup> content in irrigation water is 91.5 to 519 mg/L. Whenever values greater than 519 mg/L can severely affect irrigation equipment and crops. The concentration of HCO<sub>3</sub><sup>-</sup> and CO<sub>3</sub><sup>2-</sup> in studied water samples from Usangu paddy rice irrigation schemes were 42.7 to 189.1 mg/L and 1.10 to 48.4 mg/L, respectively (Table 48). The determined values were within acceptable range for irrigation water (91.5 to 519 mg/L). The concentration of HCO<sub>3</sub><sup>-</sup> in studied water samples were in the order of; drainages (61.0 to 189.1 mg/L), in fields (58.0 to 183 mg/L), and Channels (100.7 to 149.5 mg/L), then intakes

(42.7 to 119 mg/L), and the same trend were observed for  $\text{CO}_3^{2-}$  (Table 50). In all locations, water samples from intakes were observed to have low  $\text{HCO}_3^-$  (42.7 to 119 mg/L) and  $\text{CO}_3^-$  (1.10 to 24.2 mg/L); The  $\text{HCO}_3^-$  and  $\text{CO}_3^-$  spatial distribution was observed to vary markedly among schemes in Usangu agro-ecosystems; where Igalako, Ihahi, Ilaji, Kapunga, and Mahongole had higher values (Table 49).

#### **(iv) The concentration of $\text{NH}_4\text{-N}$ , $\text{NO}_3\text{-N}$ , and Total-N**

Nitrogen (N) is essential for plant and animal growth, but N excess in irrigation water has detrimental health and ecological effects (Diatta *et al.*, 2020; Sangeetha & Ambujam, 2021; Schullehner *et al.*, 2017; WHO, 2016). Excess N can overstimulate growth of aquatic plants and algae, leading to lake and reservoir eutrophication, contributing to fish kills, and a decline in animal and plant diversity. Thus, excess nitrate and nitrites in irrigation water is dangerous for human and aquatic life. The amount of allowable nitrate in drinking water is 50 mg/L, 0.01 mg/L for nitrite, and 0.5 mg/L for ammonium ions (Weissman *et al.*, 2020). The  $\text{NH}_4\text{-N}$  concentration in water samples from Usangu basin ranged from 8.6 to 70.0 mg/L;  $\text{NO}_3\text{-N}$  (0.1 to 33.9 mg/L) and Total N was (8.9 to 103.9 mg/L) (Table 48). Some of these values ( $\text{NH}_4\text{-N}$  and Total N) exceeded the recommended N content in drinking and irrigation water (50 mg/L). It was found that  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and total-N concentration in water samples varied with sampling points in paddy wetlands (Table 50). The determined concentration in different points was: for  $\text{NH}_4\text{-N}$  in intakes (5.7 to 29.1 mg/L), channels (8.7 to 20.0 mg/L), fields (12.9 to 35.8 mg/L) and drainages (9.5 to 70.3 mg/L). The same trend was observed for  $\text{NO}_3\text{-N}$  and Total-N (Table 50, Fig. 25). The spatial distribution of nitrogen in water samples in the study area was observed to vary from place to place (Table 49), where irrigation schemes situated in highly intensified areas, i.e., Kapunga, Mahongole, Igalako, and Mubuyuni recorded high  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and Total-N concentration in water samples (Table 49) than the less intensified schemes.

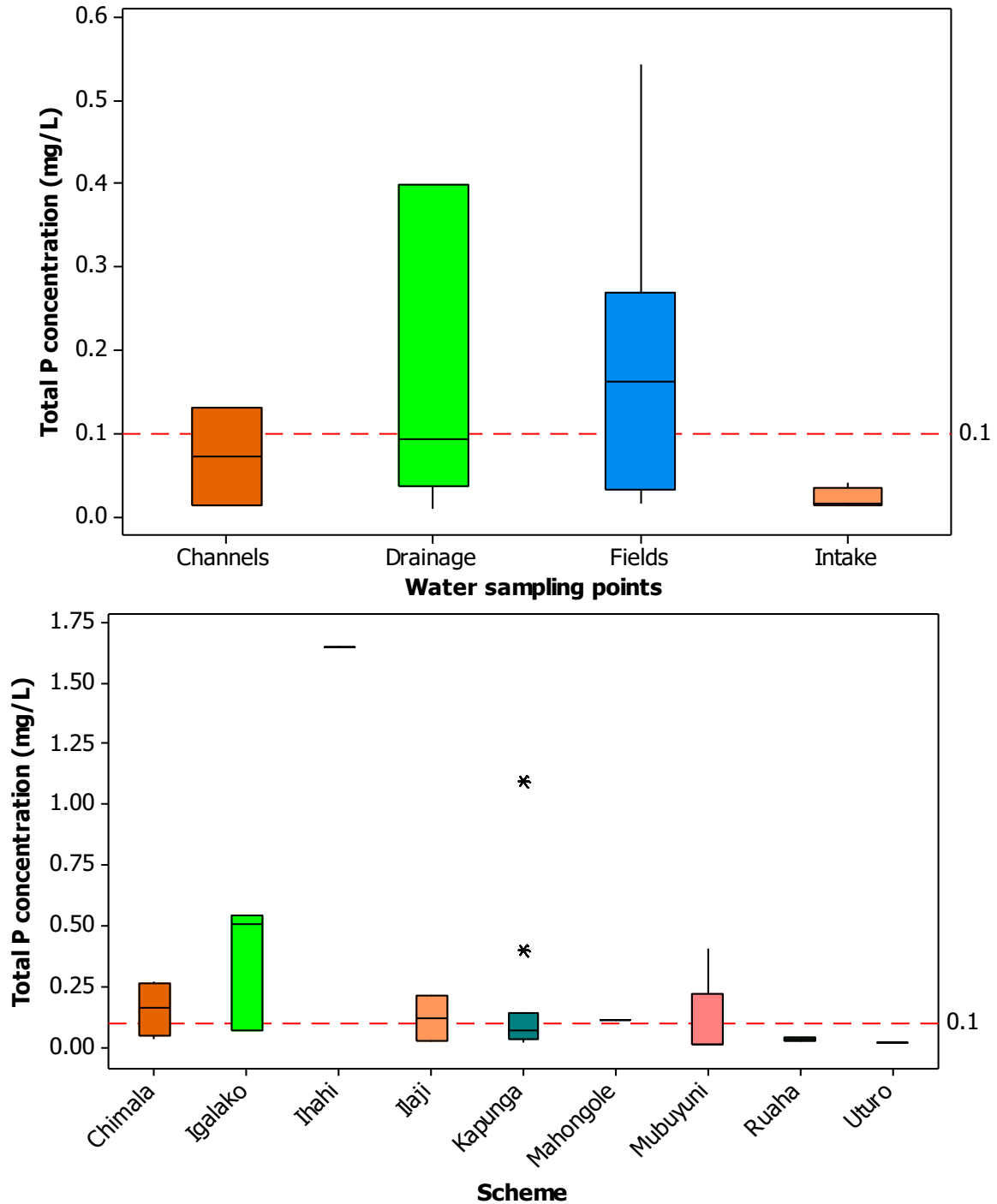


**Figure 25: Distribution of TN, NH<sub>4</sub>-N and NO<sub>3</sub>-N in different sampling points (a-c) and irrigation schemes (d-f) in Usangu agro-ecosystem**

**(v) Total phosphate in water samples in Usangu agro-ecosystem**

The total P concentration (TP) in water samples from Usangu agro-ecosystem (UA) was observed to range from 0.01 to 1.65 mg/L. Some sites had a total P above 0.1 mg/L, a proposed world limit for P concentration in freshwater reservoirs. Total P was observed to vary among sampling points where P in water increased from intakes (0.01 to 0.04 mg/L), channels (0.01 to 0.13 mg/L), in fields (0.01 to 0.54 mg/L), and in drainages (0.02 to 1.65 mg/L) (Fig. 26). The P spatial distribution in irrigation water in UA was observed to vary among schemes, where water samples from Ilaji, Igalako, Kapunga, and Chimala had high P concentrations (Table 48, Fig. 26). On the other hand, water samples from Ruaha and Uturo recorded very low

P concentrations (<0.1 mg/L) in water samples (Fig. 26). In this study, it was found that P concentration in some channels and drainages was greater than 1.65 mg/L indicating P enrichment from paddy farming areas, thus associated with reduced P for plant uptake and lead to eutrophication status of water reservoirs.



**Figure 26: The Total P concentrations among sampling points and irrigation schemes of Usangu agro-ecosystem, the red dotted line is maximum allowable P concentration in freshwater reservoirs. Above that, eutrophication of water reservoirs is expected**

**(vi) Concentration of Ca, Mg and potentially toxic element (PTEs) (Cu, Zn, and Fe)**

**Iron, magnesium, and calcium:** The concentration of Fe, Mg, and Ca in studied water samples in Usangu agro-ecosystem ranged from Fe (2.44 to 105 mg/L), Mg (38.55 to 227 mg/L), and Ca (3.86 to 22.7 mg/L) (Table 48, Fig. 27a and b ). The assessment of Ca and Mg in different water sampling points in the agro-ecosystem observed significant variation such as; Mg was in intake (60.24 to 135 mg/L), Channel (38.55 to 62.7 mg/L), Field (67.47 to 227 mg/L), and Drainages (81.93 to 125 mg/L); Ca intakes (6.27 to 135 mg/L), Channel (3.86 to 6.27 mg/L), Field (6.75 to 22.7 mg/L), and Drainages (81.19 to 125.3 mg/L) (Table 50). The spatial distribution of Fe, Ca, and Mg in water from different irrigation schemes were significant different, where irrigation schemes for instance Mahongole, Ihahi, Igalako, Chimala, and Ilaji had higher Fe (8.17 to 105 mg/L), Ca (10.42 to 17.5 mg/L) and Mg (104 to 202 mg/L) (Table 48). A ratio of Ca/Mg of less than 1 in irrigation water has been known to reduce the productivity of crops such as barley, paddy, maize, and sugar beets; the same scenario was observed in water from UA where the ratio of Ca/Mg was 0.1 (less than 1) and reverse (Mg/Ca) ratio were above 10 indicating Mg were more in irrigation water. The concentration of Fe in studied water samples from Usangu agro-ecosystem, especially in Uturo, Ruaha, and Ilaji, exceeded 5 mg/L, a maximum acceptable threshold (Table 48 and 49).

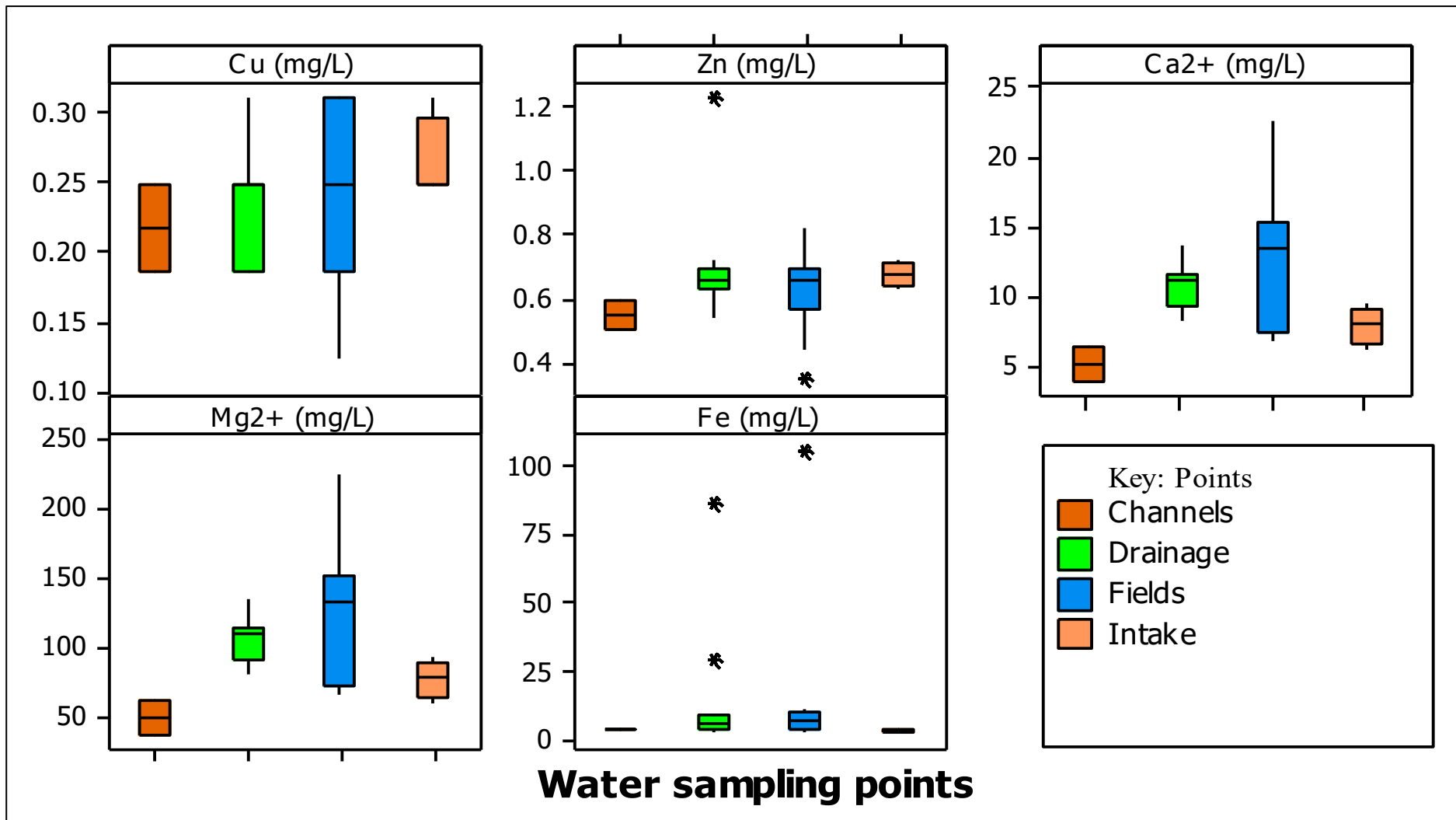


Figure 27a: The trace metals concentration distribution in water sampling points in paddy farming area in Usangu agro-ecosystem

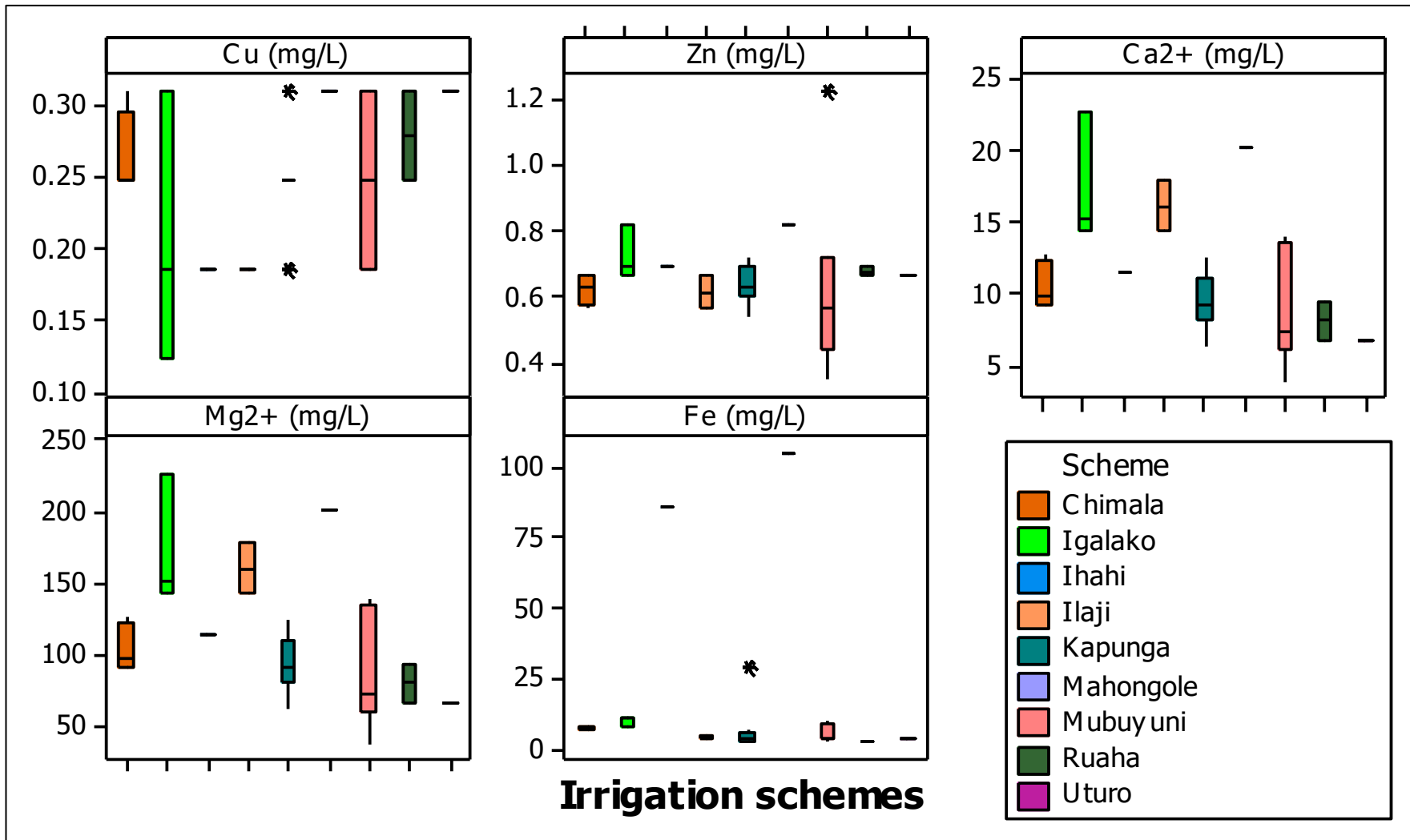


Figure 27b: The trace metals concentration distribution in water sampling points in paddy farming area in UA

The assessment of PTEs (Fe, Cu, and Zn) in different water sampling points in the agro-ecosystem observed significant variation such as; Fe in Intake (3.41 to 9.76 mg/L), Channel (3.90 to 3.98 mg/L), Field (3.41 to 105.4 mg/L), and Drainages (2.93 to 86.3 mg/L).

**Copper** and **zinc** concentrations in studied water samples were observed to vary across irrigation schemes and sampling points (Table 48 to 50). Cu and Zn concentrations in water samples were in the range of 0.35 to 1.23 mg/L for Zn and 0.12 to 0.31 mg/L for Cu (Table 48). The spatial distribution of Zn and Cu in water among schemes and sampling points was significantly different ( $P < 0.05$ ), where all schemes had Cu concentrations in water ranging from 0.12 to 0.31 mg/L. The water samples from irrigation schemes such as Kapunga, Mahongole, Ruaha, Uturo, and Chimala had higher Cu concentrations (Table 49). The observed values of Cu in all schemes were above 0.2 mg/L, the acceptable limit of Cu in irrigation water (FAO, 1985). The concentration of Cu in different sampling points were observed to be significantly different such as: intakes (0.25 to 0.31 mg/L), channel (0.19 to 0.25 mg/L), paddy fields (0.12 to 0.31 mg/L) and drainages (0.19 to 0.31 mg/L). The observed Cu concentrations were higher in water samples from fields and drainages; however, some water samples from intakes were observed to have appreciable levels of Cu. The Zn spatial distribution was observed to vary across water sampling points and schemes. All schemes had Zn concentration in the range of 0.61 to 0.82 mg/L, whereas Mahongole, Igalako, Ruaha, and Ihahi had higher values (Table 48 and 49). All water studied had Zn concentration below 2.0 mg/L, the maximum acceptable threshold of Zn in irrigation water. The concentration of Zn in different sampling points ranged from 0.35 to 1.23 mg/L, where channels, fields, and drainages recorded higher Zn concentrations than intakes (Table 50).

#### **4.1.7. Potential accumulation of PTEs from agricultural soils to plant tissues (bioconcentration) in Usangu agro-ecosystem**

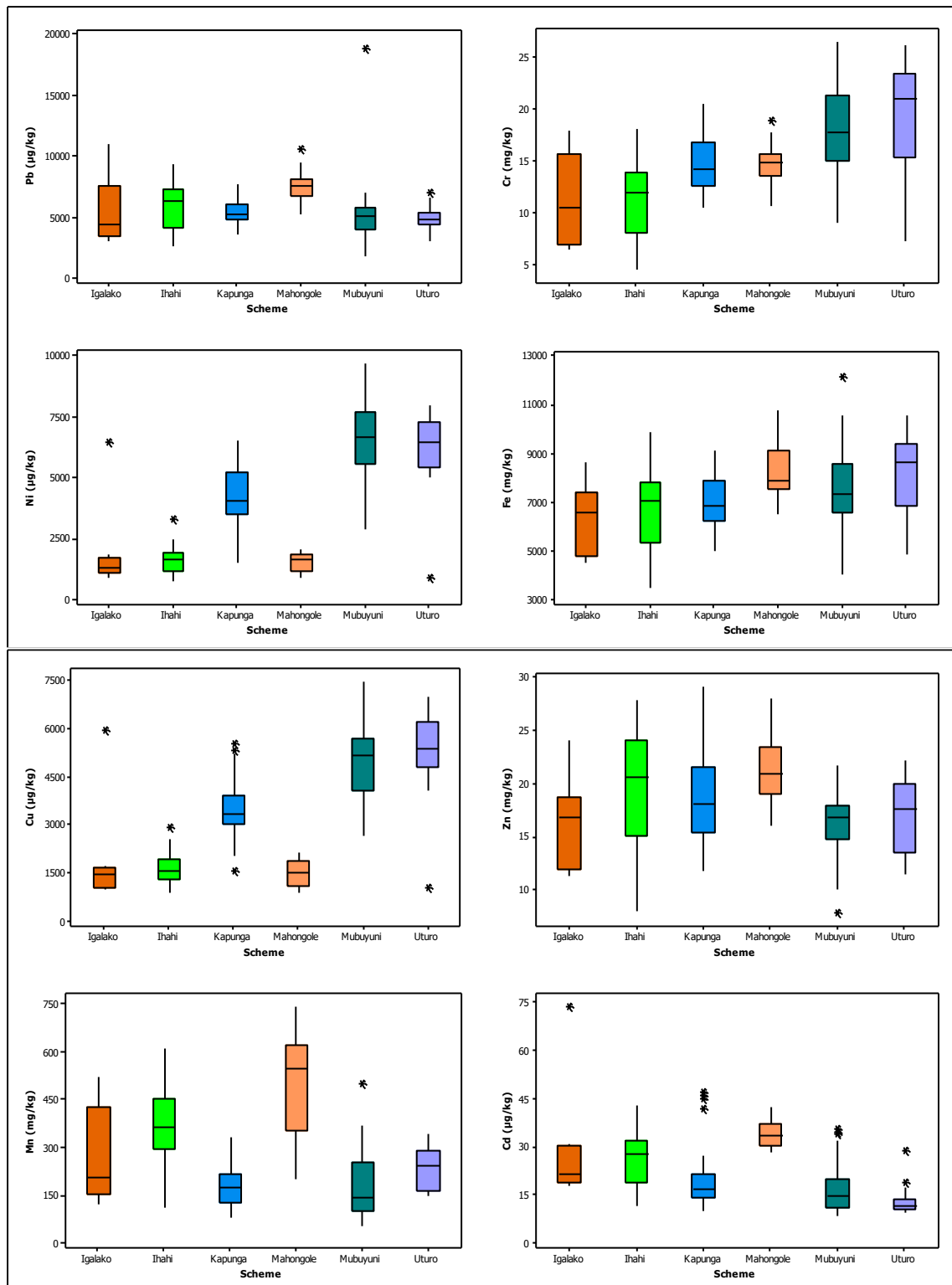
The accumulation of PTEs in agricultural soils stimulates their uptakes by plants, which could potentially affect food quality and food safety. This study studied the status, translocation and bioaccumulation of PTEs from soils to plant parts (roots, stem, and grains) in Usangu agro-ecosystem. In total, 68 soil samples and 42 paddy rice plant samples from six irrigation schemes were studied. The whole plant and its parts (grains, straws, and roots) samples were analyzed. The concentrations of Cu, Cd, Pb, Zn, Cr, Fe, and Ni, were determined in soils and plant samples to estimate accumulation, distribution, translocation and bioconcentration factors of PTEs in paddy rice as presented in Table 51 to 54.

**(i) The distribution of total PTEs in agricultural soils**

The PTEs concentration in soil samples studied from Usangu irrigation schemes where plant samples were sampled for characterization varied significantly ( $P < 0.05$ ). Where PTEs concentrations (mg/kg) in soils were Zn (18.249), Fe (7371.18), Cd (0.022), Cu (3.343), Cr (15.39), Co (2.92), Pb (5.661), and Ni (4.107). It was found that Fe and Co exceeded Tanzania's allowable limits (MAL) in agricultural soils (URT, 2007). Where out of 68 studied soil samples, approximately 99.48% of soils samples studied had Fe concentrations above permissible limits for agricultural soils. The PTEs spatial distribution in soil of studied schemes found that schemes in the lowlands had exceptional higher PTEs concentrations ( $P < 0.001$ ) such as Cu, Pb, Fe, Ni, Co, and Cr than their counterparts (Table 51). The highly intensified and commercialized schemes such as Mubuyuni, and Kapunga were observed to have higher PTEs concentrations (Table 51). Furthermore, irrigation schemes that are near or closer to residential areas such as Mahongole, and Igalako had significantly higher Zn and Cd concentrations (Table 51). All irrigation schemes had a PTEs concentration less than permissible limits except for Co and Fe, which were greater than the maximum permissible limits.

**Table 51: The concentration of PTEs and their distribution among soils from Usangu agro-ecosystem where paddy rice plant samples were sampled**

	Scheme	Cr (mg/kg)	Co (mg/kg)	Fe (mg/kg)	Zn (mg/kg)	Cd (µg/kg)	Cu (µg/kg)	Ni (µg/kg)	Pb (µg/kg)
Mean	Igalako	11.2	2.7	6245.3	16.1	29.0	1814.9	1903.1	5575.4
	Ihahi	12.1	2.0	6925.2	19.9	25.0	1960.5	2112.9	5948.8
	Kapunga	14.7	2.6	7050.1	18.6	18.5	3487.3	4225.7	5469.3
	Mahongole	14.7	3.3	8204.2	21.3	34.1	1458.9	1521.6	7633.7
	Mubuyuni	18.2	3.7	7581.6	16.1	16.8	5007.6	6513.5	5152.0
	Uturo	19.6	3.9	8297.5	16.8	13.5	5219.9	6107.5	4870.3
Minimum	Igalako	6.5	1.7	4569.6	11.3	17.9	980.7	911.2	3028.8
	Ihahi	4.6	0.5	3513.6	8.1	11.8	866.1	796.0	2661.2
	Kapunga	10.4	1.5	4996.2	11.8	10.0	1538.6	1510.8	3654.9
	Mahongole	10.7	2.0	6503.8	16.1	28.0	843.9	917.0	5271.3
	Mubuyuni	9.1	1.5	4052.6	7.9	8.3	2635.1	2924.0	1815.3
	Uturo	7.2	1.8	4857.1	11.6	9.7	992.8	886.5	3058.5
Maximum	Igalako	17.9	4.2	8651.6	24.1	73.5	5956.2	6458.4	11044.2
	Ihahi	22.8	4.5	9890.5	28.0	42.9	5929.5	7160.6	9327.1
	Kapunga	20.5	4.0	9131.9	29.2	46.9	5534.7	6546.3	7735.4
	Mahongole	18.9	4.6	10772.3	28.0	42.0	2119.5	2078.8	10557.6
	Mubuyuni	26.4	6.1	12139.8	21.8	35.3	7473.3	9673.5	18858.4
	Uturo	26.1	5.5	10550.0	22.3	28.8	6987.3	7967.1	7111.7



**Figure 28: The box plot showing PTEs distribution among soils from irrigation schemes in Usangu agro-ecosystem where paddy rice plant samples were sampled**

**(ii) The accumulation of PTEs in plant samples**

To estimate the risk of PTEs within the food chain for animals, humans, and soil invertebrates, concentrations of PTEs in whole paddy rice plant samples were determined (Table 52 and 53).

Additionally, concentrations of PTEs were determined in rice grains, straws, and roots. The total PTEs concentration (in mg/kg based on dry wt) determined in whole plant samples ranged Fe (963.51 to 27918.95), Cu (5.18 to 33.56), Cd (4.3 to 17.46), Pb (0.01 to 28.25), Zn (57.03 to 120.88), Ni (9.65 to 103.33), Mn (613.15 to 2280.98), and Cr (12.88 to 57.34) (Table 51). The measured PTEs concentration in whole rice plants was higher than that found in soil samples (Table 34). The PTEs concentration in studied plant samples varied considerably ( $P < 0.001$ ) among irrigation schemes, with greater Pb, Fe, Ni, Cu, and Zn concentrations in Mubuyuni, Mahongole, Igalako, and Ihahi. In addition, Kapunga and Uturo had higher Cd, Fe, Cr, Mn and Ni concentrations in plant samples (Table 53). The overall PTEs distribution trend in paddy rice plant samples in all studied schemes were significantly different, where higher PTEs values determined in Igalako, Mubuyuni, Ihahi, and Mahongole (Table 51 and 52), the same trend was observed in agricultural soils in the respective schemes.

**Table 52: The total PTEs (in mg/kg) accumulation in paddy rice plant samples in different schemes in Usangu irrigation schemes**

	Scheme	Cu	Zn	Fe	Mn	Cd	Pb	Cr	Ni
Mean	Igalako	21.9	111.1	48402.0	1113.7	6.5	20.4	20.9	15.0
	Ihahi	20.1	129.0	15388.1	1666.7	6.3	ND	32.3	13.9
	Kapunga	10.8	80.9	24313.0	1508.8	6.9	3.9	22.3	19.2
	Mahongole	22.7	101.5	15030.0	1665.0	6.0	18.8	19.7	17.7
	Mubuyuni	24.7	97.4	17479.9	1558.0	5.1	ND	38.7	59.4
	Uturo	17.7	89.0	7406.2	1286.8	11.6	ND	14.4	11.9
Minimum	Igalako	17.5	100.2	22390.7	613.2	4.3	20.0	13.6	12.1
	Ihahi	18.1	124.1	12906.5	1105.9	5.5	ND	18.6	13.5
	Kapunga	8.8	72.7	20787.6	1418.6	5.3	0.7	18.8	16.5
	Mahongole	19.8	94.9	8174.4	1152.8	5.7	9.4	16.2	16.2
	Mubuyuni	15.9	86.2	16223.6	1071.0	4.8	ND	21.4	15.4
	Uturo	5.2	57.0	963.5	1214.3	5.8	ND	12.9	9.7
Maximum	Igalako	24.5	118.4	95533.5	1752.0	9.0	21.0	27.8	18.6
	Ihahi	21.4	133.3	19713.3	2281.0	7.0	ND	57.3	14.7
	Kapunga	14.2	96.7	27919.0	1590.0	9.4	10.0	24.4	23.0
	Mahongole	25.7	108.0	21885.6	2177.1	6.4	28.3	23.3	19.2
	Mubuyuni	33.6	108.6	18736.3	2045.0	5.3	ND	56.0	103.3
	Uturo	30.3	120.9	13849.0	1359.3	17.5	ND	16.0	14.2

*ND means the PTEs concentrations were below detection limits*

### (iii) The potentially toxic elements distribution in paddy rice plant parts

Estimation of total PTEs in edible and non-edible parts of the plant as combination might be less useful; because not all concentrations of PTEs are available in edible parts of the plant; thus, they are less or unavailable to animals and humans. Hence determination of PTEs in roots, straws, and grain separately were conducted in this study. The PTEs were divided into three principal plant sections in this study: grains, straws, and roots. The roots indicate PTEs that can

be found to soil decomposers, while the straws represent PTEs that can be found in animal fodders. Concurrently, grains defines PTEs, which can be accessible for human and animal through rice grain consumption. PTEs concentrations varied considerably ( $P < 0.05$ ) among plant sections in all schemes, where straws and roots having greater PTEs contents than grains (Table 53, Fig. 29). The PTEs general trend were found to be higher in straws and roots than in grains. The concentration (in mg/kg) of some PTEs studied in paddy rice plant parts were; Pb in roots (ND to 9.4), straws (ND to 9.6) and grains (ND to 9.0); Zn in roots (29.3 to 68.2), straws (23.1 to 49.3), and grains (14.7 to 34.5); Cu in roots (4.5 to 22.1), straws (1.8 to 6.8), and grains (ND to 6.3); and Cd in roots (1.7 to 3.7), straws (1.7 to 8.9) and grains (1.4 to 2.2) (Table 53).

It was observed that plant samples from Mubuyuni, Ihahi, and Uturo had Pb concentration in all studied paddy rice plant parts below detection limits (ND) (Table 53), while paddy rice plant samples from Kapunga irrigation scheme were observed to have very low concentration of Pb. Example, roots (0.271 mg/kg), straws (0.274 mg/kg), and grains (0.270 mg/kg) (Table 53). The opposite scenario were determined at Igalako and Mahongole where higher Pb concentrations (mg/kg) were found, which were in range of, Mahongole (9.41 to 9.46) and Igalako (6.7 to 6.84). The Ni, Mn, Fe, and Cr concentrations in studied plant samples had similar trend as that determined in Cu, Zn, Cd, and Pb of higher values in straws and roots than in paddy rice grains (Table 53). The higher PTEs concentration in plant roots than in other plant parts indicates that translocation of studied PTEs was low or limited to roots and straws (Table 53). The concentration of PTEs in rice grains, the edible part of the paddy rice was lower than other plant parts. The concentrations of these PTEs in paddy rice plants were in the order of  $Cd > Cu > Zn > Fe > Ni > Cr > Pb$ . Furthermore, PTEs concentration in paddy rice plant tissues were in decreasing order as follows  $roots > straws > grains$  (mg/kg).

**Table 53: The PTEs concentration (in mg/kg in dry wt) among paddy rice plant parts from Usangu agro-ecosystem**

Schemes	Plant part	Cu	Zn	Fe	Mn	Cd	Pb	Cr	Ni
Igalako	Grain	6.23	34.52	10967.40	504.96	1.69	6.78	6.19	4.53
	Root	8.79	43.09	26451.82	416.02	3.12	6.78	9.36	6.73
	Straws	6.84	33.49	10982.83	192.71	1.68	6.78	5.35	3.76
Ihahi	Grain	2.72	26.10	212.72	178.60	2.05	ND	9.58	3.98
	Root	10.62	53.60	14697.60	710.65	2.45	ND	6.87	5.93
	Straws	6.81	49.25	477.78	777.40	1.84	ND	15.89	3.97
Kapunga	Grain	2.64	18.65	291.61	174.27	2.14	0.27	11.47	6.27
	Root	4.54	29.32	23365.33	431.11	1.67	0.27	6.58	4.50
	Straws	1.78	23.08	564.12	735.35	1.93	0.27	2.05	6.34
Uturo	Grain	ND	18.29	175.87	70.13	1.42	ND	10.99	5.06
	Root	22.08	68.20	12909.79	661.13	1.95	ND	5.09	4.58
	Straws	5.61	40.66	767.64	875.81	8.90	ND	2.14	4.59
Mahongole	Grain	3.00	20.67	494.03	143.51	1.60	9.42	11.52	6.10
	Root	9.76	47.74	15101.47	930.03	3.71	9.42	9.75	8.58
	Straws	7.52	39.76	889.92	680.01	1.77	9.42	2.97	5.35
Mubuyuni	Grain	2.06	14.64	202.00	151.36	1.71	ND	9.78	19.64
	Root	17.03	41.93	18092.79	630.53	2.10	ND	6.20	5.58
	Straws	5.61	40.25	498.64	809.50	1.98	ND	21.05	27.10

*ND means the concentration of the respective PTEs was below detection limits*

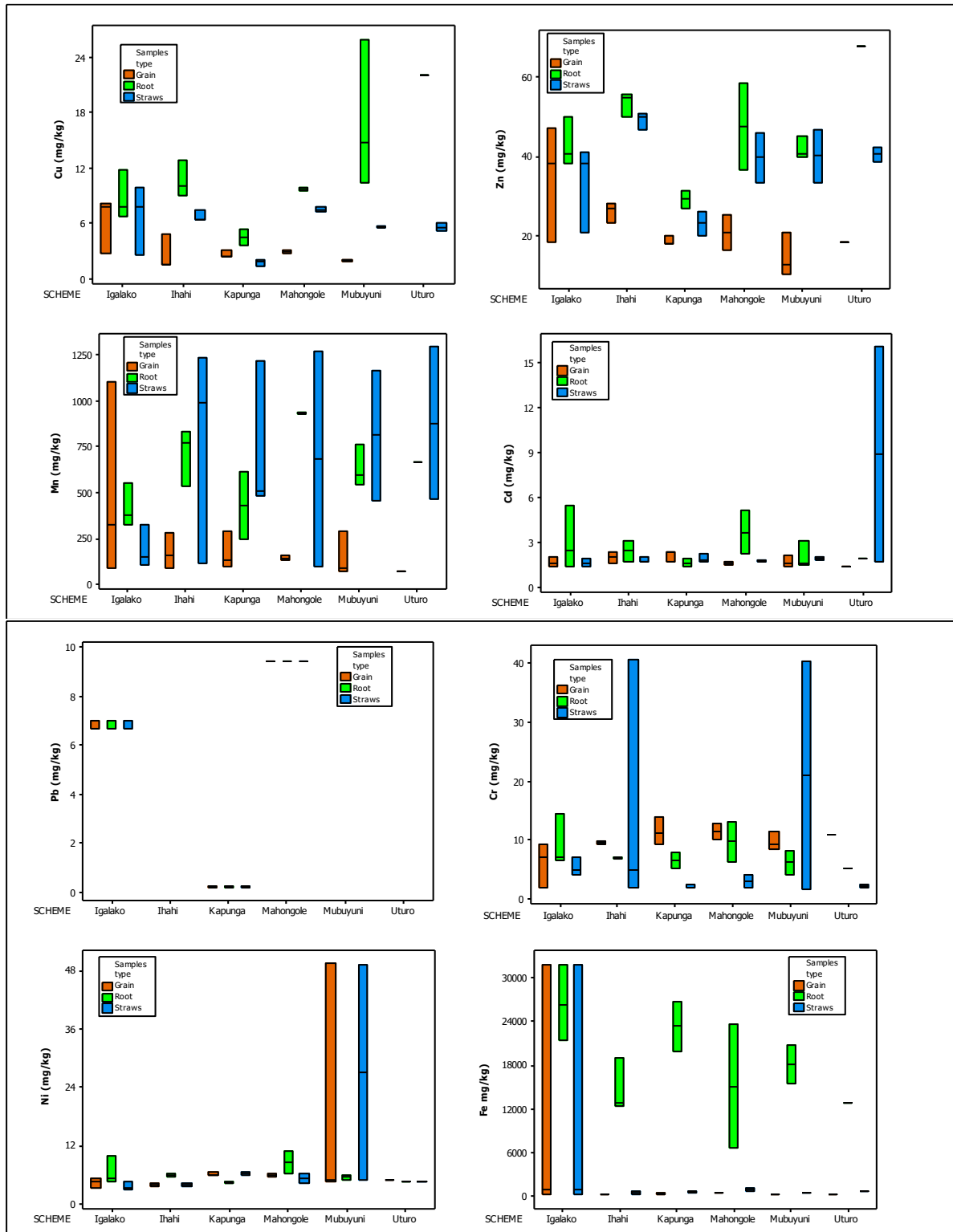


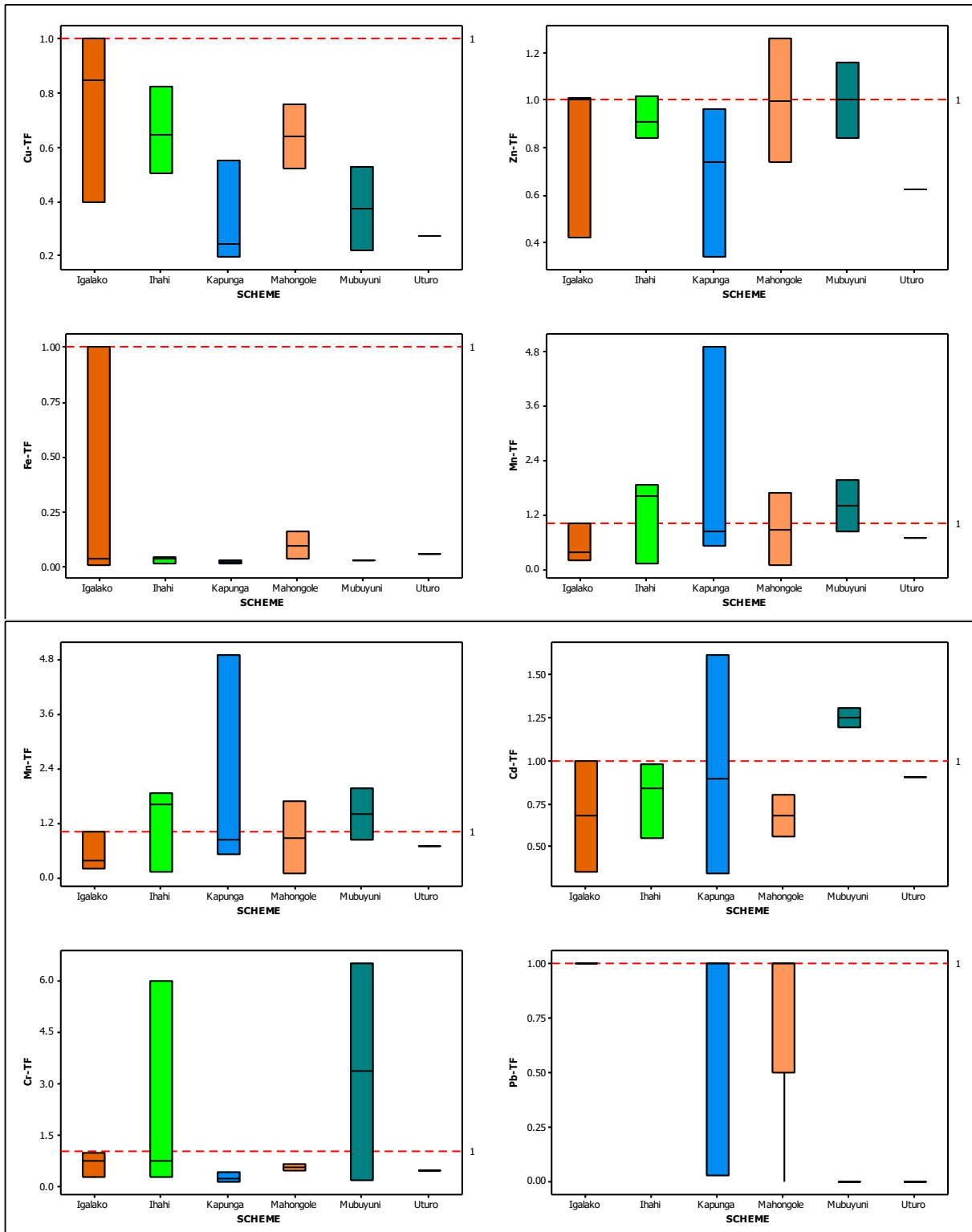
Figure 29: The spatial distribution of PTEs concentration in paddy rice parts (in grains, straws, and roots) from Usangu irrigation scheme

#### **(iv) Bioconcentration (BCF) and translocation factor (TF) of PTEs in plant samples**

Elevated PTEs in soils increase its levels in plant parts such as roots, grains, and straws, leading to health risks (Simon *et al.*, 2016). The bio-concentration factor (BCF) describes the PTEs accumulation from soil to plant tissues, while the translocation factor (TF) describes the movement of PTEs from soils through roots to above-ground biomass (shoot and straws); all these describe the availability of PTEs for plant uptakes and associated risk (Lugwisha, 2016). The BCF elucidates PTEs transfer and bioavailability from soil to plants during the growing processes. The BCF of above 1 shows that there is higher PTEs uptake in plants than in soil, while BCF of less than 1 points out that more PTEs were in soils compared with those determined in plant tissues. The PTEs in paddy rice plant samples studied from Usangu agro-ecosystem observed to vary ( $P < 0.05$ ) among irrigation schemes (Table 54). The BCF for studied PTEs were as follows; Cd (177.3 to 863.3), Cr (0.7 to 2.7), Ni (2.0 to 11.6), Fe (0.9 to 7.8), Pb (0.0 to 3.7), Zn (4.3 to 6.9), Cu (3.1 to 15.6) and Mn (3.3 to 8.4) (Table 54). Among irrigation schemes studied, all schemes (100%) had BCF above 1 for Mn, Ni, Cu, and Cd, showing that PTEs studied had more concentration accumulated in plant samples than soils. It was observed that all BCF values for Cr, Fe, Zn, and Pb were less than 1 indicating PTEs in plant sample tissues were lower compared with those in soils. Interestingly, it was observed that Igalako and Mahongole irrigation schemes had BCF above 1 for Pb in only 33.3% of the studied plant samples. Moreover, it was observed that higher BCF values for Cd (177.3 to 863.3) in all schemes (Table 56). Based on the TF, PTEs were observed to accumulate in below the ground biomass (roots) than above-ground biomass (straws) (Table 54). This study found that TF values for studied PTEs were as follows: Cr (0.27 to 2.33), Fe (0.02 to 0.35), Zn (0.62 to 1.00), Cd (0.68 to 1.25), Cu (0.27 to 0.75), Ni (0.65 to 1.15), Pb (ND to 1.00), and Mn (0.53 to 1.40) (Table 54: ). It was observed that TF values for Cr, Zn, Cd, Ni, Pb, and Mn were above 1, i.e., 33, 33, 17, 50, 33, and 50%, respectively (Table 56). This indicates that the translocation of PTEs were higher in shoots or straws than in roots which shows more transportation of PTEs from roots to straws. It was observed that Mubuyuni and Ihahi irrigation schemes had higher TF values for most of the PTEs studied.

On the other hand, the TF values for Fe and Cu were observed to be below 1 ( $TF < 1$ ) in all studied schemes indicating that the concentration of Fe and Cu was higher in roots than in straws in all studied plant samples from all irrigation schemes (Table 56, Fig. 30). The general trend for PTEs translocation factor based on this study was found that TF values for most PTEs

studied were below 1 in more than 75% of the studied schemes indicating that there was less translocation of PTEs from roots to straws or in other words more PTEs were found to be accumulated in below-ground biomass (roots) than above-ground biomass (straws and grains). Based on the determined TF for PTEs studied, it is clear that in paddy farming areas of Usangu agro-ecosystem, the risk of PTEs is less in edible plant parts; however, paddy rice straws might be associated with health risks due to the accumulation of PTEs which are usually used by grazing animals (cattle, goats and sheep) after paddy rice harvesting.



**Figure 30: The graphical representation of PTEs translocation factor (TF) in paddy rice samples from Usangu agro-ecosystem, the red dotted line is the reference point where  $TF=1$ , where neither PTEs accumulate in above-(straws) or below-ground biomass (roots)**

**Table 54: The PTEs bio-concentration (BCF) and translocation factor (TF) estimated in Usangu agro-ecosystem based on paddy rice plant samples**

Scheme	Cr <sub>BCF</sub>	Cr-TF	Fe <sub>BCF</sub>	Fe-TF	Zn <sub>BCF</sub>	Zn-TF	Cd <sub>BCF</sub>	Cd-TF	Cu <sub>BCF</sub>	Cu-TF	Ni <sub>BCF</sub>	Ni-TF	Pb <sub>BCF</sub>	Pb-TF	Mn <sub>BCF</sub>	Mn-TF
Igalako	1.9	0.68	7.8	0.35	6.9	0.81	224.2	0.68	12.0	0.75	7.9	0.65	3.7	1.00	4.0	0.53
Ihahi	2.7	2.33	2.2	0.03	6.5	0.92	253.6	0.79	10.3	0.66	6.6	0.67	0.0	ND	4.4	1.20
Kapunga	1.5	0.27	3.4	0.02	4.3	0.68	372.2	0.95	3.1	0.33	4.5	1.15	0.7	0.68	8.4	2.08
Mahongole	1.3	0.55	1.8	0.10	4.8	1.00	177.3	0.69	15.6	0.64	11.6	0.85	2.5	1.00	3.3	0.89
Mubuyuni	2.1	3.34	2.3	0.03	6.1	1.00	302.1	1.25	4.9	0.38	9.1	5.49	0.0	ND	8.4	1.40
Uturo	0.7	0.47	0.9	0.06	5.3	0.62	863.3	0.90	3.4	0.27	2.0	1.00	0.0	ND	5.6	0.70
<b>% BCF or TF &gt;1</b>	<b>83.3</b>	<b>33.33</b>	<b>83.3</b>	<b>0.00</b>	<b>100.0</b>	<b>33.33</b>	<b>100.0</b>	<b>16.67</b>	<b>100.0</b>	<b>0.00</b>	<b>100.0</b>	<b>50.00</b>	<b>33.3</b>	<b>33.33</b>	<b>100.0</b>	<b>50.00</b>

## **4.2. Discussion**

### **4.2.1. General soil properties and soil fertility in Usangu agro-ecosystem**

The success of crop production depends on different factors ranging from biotic (such as pests and diseases, good planting materials, etc.) to abiotic factors (such as climate, drought, soil fertility and other physical-chemical soil properties). Soil fertility is a major determinant of crop growth, productivity, and agro-ecosystem sustainability. In many Sub-Saharan Africa, agro-ecosystems, soil fertility has been a significant concern due to the nature of farming system commonly practised by farmers (Amuri *et al.*, 2012; Katambara *et al.*, 2016). The system involves continuous cropping and monoculture-based (mainly cereal crops), leading to continuous exploitation and plant nutrient imbalance, thus affecting soil productivity (Belay, 2015; Henryson *et al.*, 2018; Nájera *et al.*, 2015). As to other agro-ecosystems, Usangu agro-ecosystem has been affected by soil degradation, including soil erosion and soil fertility decline. The soil fertility decline is mainly due to inefficient nutrient management, which relays on application of inorganic fertilizers, which is very expensive and inaccessible to most smallholder farmers. This study characterized soil fertility status of Usangu agro-ecosystem (UA) since for the past 20 years, there was no detailed study conducted in this area to characterize soil fertility despite its essential contribution to food sufficiency and security of the country. The study characterized levels of major plant nutrients (such as Ca, N, Mg, P, and K), micronutrients (Zn, Fe, Al, Mn), and trace metals (Cu, Ni, Cr, Se, etc) and associated soil fertility parameters such as pH and organic carbon. These information are crucial in sustainable crop productivity and land management, especially during the current increasing agricultural intensification in Usangu agro-ecosystem (Mowo *et al.*, 1993; Senkoro *et al.*, 2017). The interpretation of soil fertility parameters studied were as follows:

#### **(i) Soil pH and electric conductivity (EC)**

Soil pH is an important crucial variable in soil biogeochemical processes, which control chemical, physical, and biological properties of the soil, affecting plant growth and biomass yield (Neina, 2019). The availability and mobility of plant nutrients in agricultural soils are mainly influenced by soil pH. The soil pH in various irrigation schemes in UA was 6.4 to 7.6 (Table 17), where, among 198 soil samples studied, 19 soil samples had soil pH below 6.5 showing particular soils had higher acidity conditions, which could affect plant nutrients availability such as K, N, S, Ca, P, Mg and other bases because under such pH condition,

important plant nutrients like P is fixed by Fe and Al (Sato, 2003). The low pH observed in some sampling points it might be influenced by leaching of basic cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$ ) from the plough layer leaving acidic cations  $\text{H}^+$  and  $\text{Al}^{3+}$ , but also can be due to anoxic conditions which prevent OM to mineralize and hence concentrate humic acid. The remaining soil samples had pH values in the range of 6.5 to 7.6, which are within the FAO acceptable range (6.5 to 8.5) recommended for most crop production grown in Usangu agro-ecosystem (Neina, 2019). The acidity of agricultural soils can be further exacerbated by the availability of extractable aluminium. In the study area, extractable aluminium was observed to be in a range of 93.2 to 793 mg/kg, presenting availability of extractable acidity (aluminium acidity). In such acidity, Al and Mn toxicities problems existence are expected, thus affecting crop growth and production (Ndakidemi & Semoka, 2006). As the soil pH decrease below 5.5 accelerates the solubility of Al in soil solution, and when Al reaches 2-5 mg/kg becomes toxic to roots of most sensitive crops and above 5 mg/kg aluminium becomes detrimental (toxic) to even torelant plant species. The soil pH values observed in soils from Usangu agro-ecosystem (UA) are higher compared with those recommended by Kamprath (1970) for lime application ( $\text{pH} < 5.4$ ); thus, the determined pH ranges are unlikely to cause serious plant phytotoxicity effects to crop production in the area. To ensure soil pH in UA remains within an acceptable range for increased crop productivity and soil microbes biodiversity, it is recommended to add organic manure and inclusion of legume crops to improve biogeochemical reactions and nutrient availability, especially for N, P, Ca, K, and Mg which are usually affected by low soil pH and an excess amount of Fe and Al.

Electric conductivity (EC) is a measure of alkalinity in agricultural soils; soils with high EC have higher salt ions which are likely to affect soil quality and plant nutrient availability. But also, higher EC affects the nutrient uptakes by plants as it affects the osmotic potentials, which are highly required by plants to initiate water and nutrients uptake from the soil into the plant through different pathways. The EC from soil pastes from Usangu agro-ecosystem ranged from 69.7 to 128.0  $\mu\text{S}/\text{cm}$  (Table 17), which were observed to be medium to high level that is likely to affect availability of plant nutrients. The EC determined varied among irrigation schemes, where irrigation schemes such as Ilaji, Uturo, and Igalako (196, 101, and 128  $\mu\text{S}/\text{cm}$ ), respectively (Table 17), had higher EC values which might be resulted by increased agricultural intensification and leaching of basic cations, thus accumulating soluble salts like carbonates and sodium, but also may be due to increase in concentration of salt due to the evaporation of stagnant irrigation water on the fields, which causes concentration of salts in the water and salt

deposition on the soil. Therefore, there is a need to maintain basic cations in agricultural soils of UA to ensure soil pH and electrical conductivity or salinity are within an acceptable range, which will allow better plant nutrients availability for better crop growth and production to its full potential. The EC determined in UA were observed to be low than those determined by Kashenge-Killenga *et al.* (2016) and Meliyo *et al.* (2016) in different irrigation schemes in parts of Katavi, Rukwa, Mbeya, and Iringa, where they determined extreme salinity of 4 to 15 dS/m, where the same scenario reported by Isdory *et al.* (2021) at Magozi irrigation scheme in Iringa where determined salinity of 0.3 (non-saline) to 12 dS/m (very saline), which were higher than that determined in UA, however, the EC does not seem to be very problematic yet but salt accumulation due to irrigation and high evaporation can become problematic over time.

### **(ii) Plant available phosphorus (P)**

Phosphorus (P) is among important plant nutrients required by plant in large quantities, and it does not have its replacement for better plant growth and high yields. Furthermore, P is one of the three major limitations (N, P, and water) of crop and ecosystem productivity worldwide. Thus, an appreciable amount of P in agricultural soils is essential to ensure good crop growth and high yields. The concentration of available P ( $P_{M3}$ ) from soil samples obtained from Usangu agro-ecosystem found to be in a range of 0.52 to 48.9 mg/kg (Table 17). In some sites were above 15.0 mg/kg, a recommended P level for upland soils. The study found that most of the sampling sites across Usangu agro-ecosystem had a mean  $P_{M3}$  concentration less than 15.0 mg/kg, indicative of low P concentration, which can limit crop growth and potentially requiring addition of phosphatic fertilizer to compensate the P deficiency if better crop growth and high yields must be achieved. The  $P_{M3}$  concentration among land use (conservation areas, maize, and paddy farming areas) in UA varied significantly ( $P < 0.05$ ) across land use (Table 18, Fig. 12a). The  $P_{M3}$  observed to be high in conservation areas (0.99 to 35.79 mg/kg, mean value of 13.49 mg/kg) and maize farming area (15.2 to 40.32 mg/kg, mean value of 25.73 mg/kg) than paddy farming areas (0.52 to 49.87 mg/kg, mean values of 7.7 mg/kg) (Table 18). The mean  $P_{M3}$  concentration of above 15 mg/kg was observed only in maize farming areas, signalling substantial  $P_{M3}$  concentration for crop growth. This might be associated with fertilizer and crop residues incorporation and less soil erosion observed in maize farming areas (Wasonga *et al.*, 2010). The low  $P_{M3}$  in paddy farming, even though paddy farming is a land use with higher usage of nitrogenous and phosphatic fertilizer, might be associated with high nutrient loss

through soil erosion, surface water runoffs and leaching. In addition, little addition and incorporation of crop residues in paddy farming areas might be a reason of low  $P_{M3}$ , because in paddy farming in Usangu agro-ecosystem, the crop residues are always removed out of the field to get fine tilth for easy paddy transplanting. Although conservation areas are preserved from human activities and left for natural vegetation regrow, the  $P_{M3}$  concentration determined ranging from low to high (0.99 to 35.79 mg/kg) were observed to be enough to allow natural vegetation growth and regeneration, and this is associated with plant residues decomposition. Generally, the determined mean  $P_{M3}$  values were observed to be below the average country P range (10-100 mg/kg), which were determined by Funakawa *et al.* (2012) and Kangelawe *et al.* (2007) in different parts of Tanzania.

The spatial distribution of  $P_{M3}$  concentration among irrigation schemes in Usangu observed that Igalako, Mahongole and Ihahi (Fig. 12b) had higher  $P_{M3}$  concentrations than other schemes studied; these schemes are young schemes that opened within 25 years, this has not yet been exploited to its limit, but also farmers in this schemes rely on use of organic manure and inorganic fertilizer as an option for soil fertility management which is not the case for schemes like Kapunga, Mubuyuni, Uturo and other schemes which are more than 30 years old and which only rely on the use of inorganic fertilizer but have been observed to have very low plant-available P, this may be associated with low application of organic manure and P loss through surface runoffs as results of flooding irrigation system commonly used in paddy farming. The spatial distribution of soil  $P_{M3}$  in studied irrigation schemes in UA determined higher  $P_{M3}$  (in mg/kg) in Ihahi (49.9), Mahongole (40.3), Igalako (22.1), and Kapunga (21.5) (Fig. 12b, Table 19). These schemes are situated, in lowland areas of UA, obtaining water runoffs from upper parts of Usangu, but also are among irrigation schemes that have higher agricultural intensification (Machibya & Mdemu, 2005; Ngailo *et al.*, 2016). The remaining schemes, such as Chimala, Mubuyuni, Mabadaga, Isenyela, Uturo, and Ilaji (Fig. 12b, Table 19), had lower  $P_{M3}$  concentration because these schemes are dominated by smallholder farmers who have less capital and access to fertilizer and associated with low or no organic manure applications. The determined scenario were in line with the study by Ngailo *et al.* (2016) which found that smallholder farmers with less capital to buy fertilizer and other agriculture inputs experienced low crop productivity per unit area, and their fields were observed to have insufficient levels of essential plant nutrients (N, K, and P) due to inadequate soil fertility management. As a result, soil fertility management is reliant on farmers' or landowners' ability to apply materials

and management needed to replenish plant nutrients extracted by plants in order to boost productivity and must be emphasized to ensure land productivity.

### **(iii) Exchangeable Al, Fe, and Ca**

The Al, Fe and Ca are required by plants for growth and other biochemical functions and reactions; however, extreme concentrations of Al, Ca, and Fe in agricultural soils have tendency to reduce the availability of other plant nutrients such as P due to its role in soil acidification and lowering and increase of soil pH. The Al, Ca, and Fe in Usangu agro-ecosystem were variable among land use, and determined values (in mg/kg) among land use were; in conservation areas (Fe 174; Ca 919) compared with farming areas (maize (Fe 107; Ca 1362), and paddy (Fe 214; Ca 806)) (Table 18, Fig. 13). The variability and low Ca concentration in paddy farming areas than in conservation areas may be due to continuous extraction of Ca nutrients with little replenishment.

The spatial distribution of available Ca, Al, and Fe between irrigation schemes in UA were highly variable (Table 19, Fig. 13), “where Mubuyuni, Igalako, Uturo, Kapunga, Mahongole, and Ilaji irrigation schemes were observed to have higher Fe, Al, and Ca concentration and were within the satisfactory limit (1000 mg/kg) for crop production and for availability of other essential plant nutrients (Horneck *et al.*, 1999). The study also discovered that Ca was mainly dominating cation on soil colloids, indicating that influence P available for plant absorption. The accessible Fe in soils in the study area were found to range from 81.1 to 470.5 mg/kg, which was higher than what Ndakidemi and Semoka (2006) found in Usambara mountains (where Fe ranged from 16.0 to 86.0 mg/kg) in Northern Tanzania, which were very high for plant uptake and were above the acceptable range of 0.3 to 10 mg/kg for crop production. This is likely to inhibit availability of other plant nutrients such as P, N, K, S, and Mg which is highly fixed by Fe and Al, especially at soil pH less than 5.5” (Amuri *et al.*, 2012; Karlsson & Messing, 1980; Mhoru & Anthony, 2015; Mng’ong’o *et al.*, 2021).

### **(iv) Extractable Mg, Zn, Mn, and K**

The Mg, Zn, K, and Mn are very important nutrients required for crop growth; these nutrients are usually needed in small amount, but when available at deficiency levels might affect plant growth as well as yield. Most commercially available inorganic fertilizer in Tanzania does not include micronutrients in their formulation until recently, when few fertilizer companies have started to include micronutrients in their formulations (Senkoro *et al.*, 2020). This was the case

because previously, the role of micronutrients in plant growth and yield were underestimated, but in degrading arable soils with less micronutrients, the role of micronutrients has been observed to be very important from vegetative crop growth to reproductive stages (Senkoro *et al.*, 2017). The concentration of K, Mg, Mn, and Zn in agricultural soils from Usangu agro-ecosystem were found to vary among land use and irrigation schemes (Table 20 and 21), “where the overall trend were K (28.8 to 1484.2 mg/kg, and mean of 420.8 mg/kg), Mg (42.2 to 1069.2 mg/kg, and mean of 246.7 mg/kg), Zn (0.34 to 7.5 mg/kg, and mean of 2.3 mg/kg), and Mn (12.85 to 503.1 mg/kg, and mean of 142.4 mg/kg) (Table 20). The spatial K, Zn, Mg, and Mn distribution varied among land use (Table 20, Fig. 15), where higher K observed in maize farming areas (647.1 mg/kg) and conservation areas (500.0 mg/kg) than in paddy farming areas (399.8 mg/kg). The same trend determined for Zn and Mn, while higher Mg determined in conservation areas (300.9 mg/kg), compared with maize farming (286.9 mg/kg) and paddy farming (238.6 mg/kg) areas. Based on the suggested critical levels for most crops of 2 cmol/kg (400, 240, and 780 mg/kg for Ca, Mg, and K, respectively) (Schwartz & Corrales, 1989), some locations had a concentration of K, Mg, Mn, and Zn below critical levels; thus it require addition or supplemental nutrients to ensure maximum crop growth and productivity. The ratio of available magnesium and potassium (Mg:K ratio) is important in estimating the availability of Mg and K for plant uptake (Ndakidemi & Semoka, 2006). The computed Mg:K ratio in soils from Usangu agro-ecosystem were less than 2, a recommended value for better K and Mg availability to ensure optimum crop growth. Henceforth, Mg and K were available at insufficiency levels constraining crop growth and yield in agro-ecosystem. Therefore, fertilizer and other materials which are rich in Mg and K must be applied to guarantee optimal crop growth and high yields (Farina *et al.*, 1992). In all soils, available Mn ranged from 3.0 to 384 mg/kg, which were generally greater than Mn proposed insufficiency level of 2.0 to 5.0 mg/kg (DTPA), where values of greater than 140 mg/kg are considered excess Mn in agricultural soils (Sillanpää, 1982). In this study, five sites ((Ihahi (226.9 mg/kg), Mahongole (201.3 mg/kg), Igalako (159.1 mg/kg), Isenyela (147.9 mg/kg), and Ilaji (141.6 mg/kg)) were observed to have excessive amount of Mn which could potentially lead to manganese toxicity to crops, and other 5 sites or schemes were determined to have Mn deficient levels (Table 19). Available Zn in Usangu agricultural soils was in the range of 0.34 to 7.5 mg/kg, which were higher than proposed Zn deficiency range (0.4 to 0.6 mg/kg), where anything greater than 10 to 20 mg/kg is considered as the excess amount. Therefore, Zn concentrations determined in agricultural soils in Usangu agro-ecosystem were sufficient for most crops growth” (Ndakidemi & Semoka, 2006).

#### **(v) Total soil organic carbon**

Soil organic carbon (OC) is an important in plant nutrient availability in agricultural soils and determines the availability of other plant nutrients as it influences minerals solubility, charges, CEC, and soil pH. In addition, soils with high organic carbon have high soil microbial biodiversity such as fungi and bacteria as well as soil invertebrates, including earthworms and termites, which are very important in soil organic matter mineralization and nutrient re-cycling (Ayuke *et al.*, 2011). On the other hand, OC is a proxy for organic matter (OM); which upon mineralization, it releases plant nutrients such as N, P, and S. From collected soil samples from different sampling points in Usangu agro-ecosystem, total OC ranged from 0.37 to 2.37%, with a mean value of 1.51% and were classified to be low to medium (Table 17). The spatial distribution of soil organic carbon among irrigation schemes was observed to vary significantly where Ilaji (2.37%), Uturo (1.99%), Mahongole (1.37%), and Mabadaga (1.33%) were observed to have higher OC compared with other schemes which recorded OC<0.8%. Due to the fact that OC is a key in maintaining nutrients, soil health, and biodiversity; therefore, soils with low OM content, as observed in Usangu agro-ecosystem, are likely to have plant nutrients deficiency because of poor microbial activity and reduced nutrient cycling and more susceptible to erosion, worsening soil structure (Ebrahimi *et al.*, 2021). The OC determined in UA were observed to be lower than those determined by Funakawa *et al.* (2012) in different parts of Tanzania which were in a range of 2.13 to 152 g/kg; this might be associated with low organic matter or crop residues incorporations.

Additionally, OC content determined in Usangu agro-ecosystem (0.37 to 2.37% which is equivalent to 0.37 to 23.7 g/kg) were generally below 20.0 g/kg, a proposed critical level of soil organic carbon, thus, determined OC in Usangu agro-ecosystem were below recommended levels. This indicates that agricultural soils from Usangu agro-ecosystem are experiencing soil quality degradation and soil microbial activity reduction (Funakawa *et al.*, 2012; Ndakidemi & Semoka, 2006). Furthermore, higher OC content in maize and conservation areas than in paddy farming areas is illustrated by higher crop residues and organic manure application and decaying plant material that were abundant during sampling period. Thus, any practices which could potentially increase soil organic carbon and organic matter in agricultural soils in Usangu agro-ecosystem is highly recommended to improve soil fertility and microbial activity, that could be possible through crop residues and organic manure application in both maize and

paddy farming areas and inclusion of cover crops and leguminous plants, especially during dry season to utilize the residual moisture after paddy harvesting.

#### **(vi) Total nitrogen (Total N)**

From the studied soils, the total N were in a range of 0.29 to 1.73 g/kg, where all studied soils (100%) were found to have total N below 2.0 g/kg, a recommended critical level for at least optimal crop growth (Ndakidemi & Semoka, 2006). Thus, studied soils from Usangu agro-ecosystem were observed to have deficient levels of N to support better plant growth. Despite the fact that all schemes had total N levels below critical levels; some irrigation schemes had considerable total N concentration (g/kg) such as Ilaji (1.73), Uturo (1.65), Mahongole (1.10), and Mabadaga (1.05), whilst other schemes had total N concentration less than 0.29 g/kg (Table 17). This shows that N concentration in agricultural soils from most irrigation schemes studied was not sufficient to support better plant growth. The determined N concentration in UA were observed to be lower compared with the average total N (0.12 to 13.7 g/kg) determined by Funakawa *et al.* (2012) in ninety-five (95) topsoil samples collected from different regions of Tanzania; this might indicate the temporal decrease in total N in agricultural soils of Tanzania because it is about 20 years since that analysis were conducted by Funakawa. Therefore, application of inorganic nitrogenous fertilizer and organic manure rich in N, like poultry manure, is recommended to ensure better plant growth and yields. Farmers in UA utilize fertilizers on their fields, but mostly mineral fertilizer, which requires yearly application and is limited by rising prices. As a result, the problem of N deficit is expected to worsen in the future (Ngailo *et al.*, 2016). Since N is one of the vital elements for plant growth, needed for optimum crop production in UA, areas with total N below the required amount can be supplemented with organic and mineral fertilizer or by including legume crops that can fix nitrogen from the atmosphere, but also producing crop varieties with higher N use efficiency will be the best and most sustainable option to ensure high yield from low N uptake.

#### **(vii) Micronutrients accumulation and distribution**

The micronutrients such as Cu, Cr, Co, Mo, and Ni are useful for plant growth at low concentrations or doses; however, at higher concentrations, they are toxic to plants and plant product users and can inhibit soil microbial activity, thus affecting nutrient cycling. The Cu, Co, Ni, Cr, and Mo concentrations easily available for plant uptake were determined across land use and irrigation schemes in UA (Table 18 and 19) were as follows.

**Copper (Cu):** The concentration of available Cu was observed to range from 0.03 to 7.21 mg/kg (Table 20 and 21), which were within acceptable recommendation of 0.2 mg/kg, a minimum amount of Cu required for better plant growth; any values below this threshold will provide insufficient Cu for plant growth (Lindsay & Norvell, 1978). Almost all soils studied had a Cu concentration above proposed minimum limit for crop productivity, indicating that available Cu in the study area were in sufficient concentrations for plant growth (Table 20). The Cu concentration among land use studied was observed to vary significantly ( $P < 0.05$ ); this might be associated with management activities that are conducted in land use. For example, Cu concentration in reserved or conservation areas were observed to range from 0.15 to 3.67 mg/kg; in maize farming, 0.52 to 0.97 mg/kg; and paddy farming 0.03 to 7.21 mg/kg. The study found a higher concentration of available Cu in paddy farming areas than in maize and reserved areas; this is likely to be influenced by management systems such as application of Cu-based agrochemicals such as fertilizer and pesticides, which is commonly used in paddy farming areas than maize. The Cu concentration determined in UA agricultural soils were observed to be very low compared with values determined by Mathew *et al.* (2016), who determined Cu concentration in agricultural soils of  $> 8.4$  mg/kg along the slope of Mountain Kilimanjaro. The increased Cu concentration in agricultural soil has both positive and negative impacts on crop productivity (Fagnano *et al.*, 2020). Highly intensified schemes in UA were observed to have higher Cu concentrations (mg/kg) in soils (i.e., Uturo (4.14), Mubuyuni (3.44), Mabadaga (2.11), Kapunga (1.83), and Ilaji (1.53)) than those which are less intensified (i.e., Ihahi (0.81), Mahongole (0.68), Igalako (0.55), Isenyela (0.31)) (Fig. 16). This indicates that farming and its associated management practices determines Cu concentration and distribution in agricultural soils in Usangu agro-ecosystem.

**Cobalt (Co):** The Co is a beneficial micronutrient required by plants at micro-doses as it is important in numerous enzymes, boosts seed drought resistance, and is required by bacteria in legumes for nitrogen fixation (Akeel & Jahan, 2020). The agricultural soils from Usangu agro-ecosystem were observed to have appreciable Co concentrations which were 45.2 to 2684.3  $\mu\text{g/kg}$ , which varied significantly among land use, i.e., conservation areas (135.9 to 1523.9  $\mu\text{g/kg}$ ) (Fig. 16), maize farming (435.6 to 639.1  $\mu\text{g/kg}$ ), and paddy farming (135.9 to 2684.3  $\mu\text{g/kg}$ ). The spatial distribution of Co over UA was significantly different between schemes (Fig. 16), where Ilaji (135.9 to 468.6  $\mu\text{g/kg}$ ), Chimala (666.8 to 719.3  $\mu\text{g/kg}$ ), Ihahi (164.2 to 1045.4  $\mu\text{g/kg}$ ), Igalako (365.4 to 883.5  $\mu\text{g/kg}$ ), and other schemes as shown in Table 21 recorded higher values. The values of Co found in this study were sufficient to allow or support

plant growth; however, some sites had extremely high values, potentially posing phytotoxicity effects to plants and microbial diversity in the soil.

**The available Cr, Mo, and Ni:** Concentration of available Cr, Mo, and Ni in agricultural soils from Usangu agro-ecosystem were observed to vary among land use and locations of irrigation schemes. The general trend ranged from; Cr (0.0 to 222.8  $\mu\text{g/kg}$ ), Mo (0.0 to 65.9  $\mu\text{g/kg}$ , and Ni (25.2 to 4497.3  $\mu\text{g/kg}$ ) across irrigation schemes and land use in the study area (Table 20 and 21). The spatial distribution of Cr, Mo, and Ni among studied schemes were higher at; Cr was higher (in  $\mu\text{g/kg}$ ) at Mabadaga (99.1), Mubuyuni (84.9), Uturo (55.8), Ilaji (46.1), and Kapunga (39.6) (Table 21). At the same time, higher values (in  $\mu\text{g/kg}$ ) of Mo were determined at Ihahi (11.80), Isenyela (16.44), and Mahongole (5.67). The assessment of Cr, Mo, and Ni in soils from different land use was higher in farming areas than in reserved areas such as; Cr in conservation (0 to 85.7  $\mu\text{g/kg}$ ), paddy farming (0.9 to 222.9  $\mu\text{g/kg}$ ), and maize farming areas (0 to 18.5  $\mu\text{g/kg}$ ); Mo in paddy farming (0 to 65.9  $\mu\text{g/kg}$ ), in maize farming (5.0 to 22.1  $\mu\text{g/kg}$ ), and conservation areas (0.0 to 20.4  $\mu\text{g/kg}$ ), where the same trend was observed for Ni (Table 21). The increased levels could be linked to fertilizer, pesticides, herbicides, and degradation of plant components and residues, but the observed values were found to be sufficient to maintain plant development and reactions (Souri *et al.*, 2018). The determined micronutrients levels in Usangu agro-ecosystem were observed to be higher compared with values obtained in other parts of Tanzania, such as Kilimanjaro and Tanga as determined by Mathew *et al.* (2016) and Mowo *et al.* (2006), such as mean values for Fe, Mn, Zn and Cu concentrations in topsoil in Kilimanjaro were 130.4, 193.4, 2.8 and 8.8 mg/kg, respectively.

Generally, the study found vital variations in plant nutrients in UA, where major soil plant nutrients such as N, P, K, Ca, and Mg were in deficient amounts, thus limiting better crop growth in UA. Some soils were found to have appropriate quantities of exchangeable Al and metallic micronutrients (Mo, Cu, Fe, Co, Zn, Ni, and Cr). The findings show that sustaining soil fertility in UA is difficult, which could affect agricultural output and sustainability. Mineral nutrients intervention measures must be implemented in regions where plant nutrients are insufficient to address the issues; this may include application of organic manure, inorganic fertilizers, and inclusion of legumes, and where possible use of fallowing practice can be implemented.

#### **4.2.2. Current soil phosphate status and its availability to plants in UA**

In most tropical soils such as those of Usangu agro-ecosystem (UA) are usually highly weathered with high concentration of P complexants such as Al, Ca, and Fe, the availability of P for plant are usually a challenge. Most tropical soils have reported to have high total P concentration but the fraction of total P available for plant uptake (bioavailable P) is very low, the same results determined in the current study. For that reason, this study characterized P concentration in different fractions in agricultural soils to estimate status and availability of P as influenced by land use and associated management as described hereunder.

##### **(i) Total soil phosphate (TP) in Usangu agro-ecosystem**

The TP concentration in agricultural soils was observed to vary across land use and irrigation schemes, but it was in the range of 63.1 to 1350.1 mg/kg (Table 22 and 23). Based on land use, TP was observed to be high in paddy farming areas (63.1 to 1350.9 mg/kg) than in other land use (Maize farming 553.3 to 668.5 mg/kg and conservation areas 129.5 to 589.6 mg/kg) (Table 23). The higher TP in farming areas is associated with farming management practices, including organic and inorganic fertilizers applications, which increase P as well as Fe, Al, and Ca, which are important P adsorbents. The spatial distribution of TP in Usangu agro-ecosystem varied among schemes (Table 22), where some schemes were observed to have high TP concentration (in mg/kg) such as Ihahi (790.7), Kapunga (1350.9), Mahongole (814.3), Igalako (536.1), Ilaji (589.6), Uturo (556.1), and Mubuyuni (435.1) which are rated as highly intensified irrigation scheme in Usangu basin. In addition, in this study it was found that land use and irrigation schemes that had higher Mg, Al, Ca, and Fe concentrations were found to have higher TP concentrations. This indicates there is a positive correlation between TP and concentration of Mg, Fe, Al, and Ca in agricultural soils. Higher TP concentration determined in Usangu agro-ecosystem may be intensified by high Al, Fe, Ca, and Mg concentration because these elements are highly responsible for P adsorption and fixation in soils, thus reducing P availability for plant uptake and loss to the environment. On the other hand, lower TP (in mg/kg) were determined in soil samples from Mabadaga (203.7), Chimala (177.9), and Isenyela (138.1) (Table 22). The same trend was observed to be in line with the concentration of Mg, Fe, Ca, and Al. This study was in line with the study conducted by Adhikari *et al.* (2017), who studied total P in agricultural soils from Japan, Afghanistan, and France, where the negative correlation were found between Al, Fe, Ca, and soluble P while there was a positive correlation with TP. Thus, Al, Fe, and Ca concentration, SOC and clay content in agricultural

soils might favour P accumulation in agricultural soils due to high P fixation and its unavailability for plant uptake; however that role might have negative impacts on agricultural productivity as most of the fixed P is not available for plant uptake but just increase legacy P in agricultural soils (P ageing), thus further researches on how to utilize legacy P in most tropical soils has to be conducted.

## **(ii) Soil bioavailable P (B-P) in Usangu agro-ecosystem**

The B-P concentration which is easily available P for plant uptake in agricultural soils in Usangu agro-ecosystem as determined by M3 method (Kleinman & Sharpley, 2002; Nasukawa *et al.*, 2019) are easily available for plant uptake; this fraction also represents a concentration of P which can be easily lost to the environment when poorly managed. From the analysis, “the B-P concentration in agricultural soils among land use and irrigation scheme in UA were found to range from 0.52 to 49.87 mg/kg (Table 22), which varied among land use (maize, paddy and conservation areas), such as; maize farming area (15.20 to 40.32 mg/kg), conservation areas (0.99 to 35.79 mg/kg), and paddy farming areas (0.52 to 49.87 mg/kg). The determined B-P was lower in farming areas, especially in paddy farming areas (7.70 mg/kg) which associated with extensive farming practices involving deep ploughing and less crop residues incorporation compared with maize farming areas (25.73 mg/kg) and conservation areas (13.49 mg/kg), where there is less disturbance in soil structures. The paddy farming areas were observed to have higher concentrations of Al (294.1 mg/kg), Fe (806.89 mg/kg), Ca (214.81 mg/kg), and Mg (238.59 mg/kg) (Table 22), which consequently reduced B-P availability in agricultural soils. The Mg, Al, Ca, and Fe concentrations were significantly negatively correlated ( $P < 0.05$ ) with B-P (Table 24) because they increase the capacity of the soil to hold or fix P, making it unavailable for plant uptake (Barrow *et al.*, 2020; Barrow & Debnath, 2015).

The B-P spatial distribution in Usangu agro-ecosystem evidenced that some schemes had higher B-P concentrations such as Uturo (18.1 mg/kg), Ihahi (49.1 mg/kg), Kapunga (21.5 mg/kg), Mahongole (40.3 mg/kg), Igalako (22.1 mg/kg), and Mubuyuni (18.6 mg/kg). These values were observed to be optimal (26 to 35 mg/kg) to higher (36 to 45 mg/kg) for crop requirements in the area (Mallarino *et al.*, 2013; Sims *et al.*, 2002). However, other schemes recorded B-P deficient in agricultural soils; this includes Chimala (6.2 mg/kg), Ilaji (8.4 mg/kg), Isenyela (6.9 mg/kg), and Mabadaga (1.9 mg/kg)” (Mng’ong’o *et al.*, 2021). Thus there is a need for additional application of P fertilizer to accommodate plant growth. Based on recommended level of B-P (Nishigaki *et al.*, 2018) in agricultural soils “(Low:0 to 25 mg/kg,

optimum: 26 to 35 mg/kg, high: 36 to 45 mg/kg and very high: >46 mg/kg)” (Mallarino *et al.*, 2013); some sites had low B-P concentration (<25 mg/kg) while other sites such as Mahaongole (40.32 mg/kg) and Ihahi (49.87 mg/kg) had points with high to very high B-P concentrations, respectively, thus does not require additional P application to reduce production cost and loss to the environment. This observation determined in this study was in line with the study by Nishigaki *et al.* (2018), who found low bioavailable P and P availability due to high fixation of added P from P-fertilizer due to high concentration of Ca, Al, and Fe in different parts of Southern Tanzania.

### **(iii) The P bioavailability among land use**

The concentration of P in agricultural soils from various land uses in the study area revealed a substantial difference in the amount of P contained in soil samples compared with the amount available for plant uptake among land use. The concentration of P that is not accessible for plant uptake, which is either fixed or complexed by metals ions (Po), was estimated by subtracting B-P from TP, based on the total P (TP) and bioavailable P (B-P) the availability of P in the study area were determined (Table 22). In this dissertation, this amount was termed as complexed P (Po). The comparison of TP and B-P in different land-use observed that Po was very high, indicating that B-P concentration compared with TP determined was very low (<10%); thus high concentration of legacy P in agricultural soils exists (Table 22 and 23). The determined TP and B-P concentrations in three land-use were; conservation areas (129.5 to 589.7 mg/kg for TP, 0.9 to 35.8 mg/kg for B-P), paddy farming areas (63.1 to 1350.1 mg/kg for TP, 0.5 to 49.9 mg/kg for B-P), and maize farming areas (353.3 to 668.5 mg/kg for TP, 15.2 to 40.3 mg/kg for B-P) (Table 22). Higher TP values in paddy and maize farming areas and very low bioavailable P (0.82 to 6.03% of the TP) indicate that paddy and maize farming activities negatively influence P availability in agro-ecosystem. The situation observed in paddy farming areas, where low B-P concentration and higher Po (62.60 to 1301.03 mg/kg) are observed in agricultural soils despite higher determined TP, indicates that paddy farming and associated activities highly negatively influenced per cent of bioavailable P (0.82 to 3.69%) compared with maize farming areas which had 4.30 to 6.03% of P bioavailability, while conservation areas had 0.72 to 6.07% of P bioavailability, additional possible reasons for low B-P apart from higher concentration of Al, Fe, Mg and Ca are soil erosion, surface runoffs and leaching due to flooding irrigation system common in the area.

The spatial distribution B-P and Po in agricultural soils were observed to vary significantly among schemes (Table 23), where the general trend in per cent of P bioavailability ranged from 0.9 to 6.3%; and high P bioavailability were observed in Ihahi (6.3%), Isenyela (5.1%), Mahongole (4.9%), and Igalako (4.1%). However, some schemes recorded a very low P bioavailability compared with determined TP, such as Ilaji (1.4%), Kapunga (1.6%), and Mabadaga (0.9%). This indicates that these schemes experience P deficiency requiring addition of P from fertilizers and other P rich materials. Furthermore, it was observed that some irrigation scheme, for example, Kapunga irrigation scheme, which is observed to have high TP, low B-P and high Po indicates that the phosphatic fertilizer added in these areas are less utilized by plants (0.82 to 3.69%) and the rest is fixed in soil colloids thus limiting the efficient use of added fertilizer and resulting to low fertilizer returns. This might be exacerbated by intensive deep ploughing which is common to these irrigation schemes, but also soil erosion, surface runoffs and leaching is possible addition reason for low B-P and this study was in line with the study by Zhang *et al.* (2021), which observed that deep ploughing reduced P availability in three sub-tropical agricultural soils (Oxisol, lixisol, and Vertisol) in Australia. Thus, farm management in UA might be responsible for reduced P bioavailability for plant productivity. On the other hand, high P bioavailability in conservation areas than farming areas indicates that changes of natural land to cultivated land reduce P bioavailability due to the fact that these transformations alters soil physics and chemistry, which are an important factor for P bioavailability and its sustainability. Thus, good agronomic practices such as reduced tillage practices which ensure reduced soil disturbance, alternate wetting and drying irrigation practice may be employed to ensure P bioavailability for increased crop productivity and increased fertilizer returns.

#### **(iv) The current soil P status ( $P_{M3}$ ) and availability in Usangu agro-ecosystem**

Based on TP and B-P concentrations determined in agricultural soils from UA, The current  $P_{M3}$  concentration in agricultural soils was observed to differ between irrigation schemes, ranging from 0.52 to 49.9 mg/kg, which were observed to be lower in most sites and higher in few sites (Table 18 and 19). Among irrigation schemes, higher  $P_{M3}$  values (mg/kg, maximum values) found in Mahongole (40.3), Ihahi (49.9), Uturo (18.1), Igalako (22.1), Mubuyuni (15.9) and Kapunga (21.5). Where locations with high  $Al_{M3}$  and  $Fe_{M3}$  concentration were observed have a low available  $P_{M3}$  concentration and had a negative correlation ( $P < 0.05$ ) with available  $P_{M3}$ , therefore, Al and Fe in agricultural soils influence availability of  $P_{M3}$ . The  $P_{M3}$  spatial

distribution among land use were higher in farming areas, i.e., paddy farming (49.87 mg/kg) and maize farming areas (40.32 mg/kg) than in conservation areas (35.79 mg/kg). The study found that the current P status were low in many sites (<25 mg/kg) whilst other few sites such as Mahaongole (40.3 mg/kg) and Ihahi (49.8 mg/kg) had high to very high  $P_{M3}$  (Mallarino *et al.*, 2013). The current determined  $P_{M3}$  were observed to be higher and lower in some sites compared with the concentration determined by Funakawa *et al.* (2012) in topsoils from different parts of Katavi, Iringa, Rukwa, and Ruvuma regions where determined available P were in a range of 10 to 100 mg/kg.

The ratio of  $P_{M3}/(Al_{M3}+Fe_{M3})$ , “which estimates the availability of  $P_{M3}$  for plant uptake were observed to be 0.004 to 0.16, ranging from below optimum ( $P_{M3}/(Al_{M3}+Fe_{M3})<0.06$ , optimum ( $P_{M3}/(Al_{M3}+Fe_{M3})$ ) 0.06 to 0.11, and above optimum  $P_{M3}/(Al_{M3}+Fe_{M3})>0.15$ ” (Sims *et al.*, 2002). This study evidenced that land-use change in Usangu agro-ecosystem directly influences bioavailability of important plant nutrients such as P in agricultural soils by modifying the nutrients cycles and soil chemistry, which can directly or indirectly affect bioavailability of essential plant nutrients like P in agricultural soils. The determined TP and B-P in different land-use indicated that some areas are experiencing P deficiency which could be a result of high fixations and adsorption. Where split fertilizer application and reduced tillage are recommended to increase P bioavailability, reduce legacy P, and P loss to the environment. This study raises awareness about how phosphate bioavailability in agricultural soils for plant absorption can be affected by land-use change and associated management, resulting in legacy P, where legacy P can be a hot spot (source) of P loss to the environment, resulting in eutrophication, especially in places prone to soil erosion and high surface runoff as UA which has strong hydrological connections.

#### **4.2.3. Soil phosphate sorption capacity (PSC) and phosphate saturation degree (PSD) indicator as an estimate risk of P fixation and loss from UA**

##### **(i) Soil phosphate sorption and sorption capacity (PSC)**

Sorption is the ability of the soil to adsorb and hold plant nutrients such as P in the soil colloids to make it held for plant uptake and reduced loss to the environment. The PSC of agricultural soils indicates the amount of P which can be held in agricultural soils and be available for plant uptake but also PSC indicates how unlikely the available P can be available for loss to the environment through leaching and surface runoffs (Kleinman *et al.*, 2015). Agricultural soils

with high PSC hold added P from fertilizer well, and little loss is expected hence making more P available for agricultural uptakes. However, extreme values of PSC cause added P to be held tightly in agricultural soils, thus affecting P availability for plant uptake. Again, it can also bind all fertilizer and not release it for agriculture. This is a big issue in Africa especially. There are optimal PSC values wherein P is bound but also not too strongly so it is not available for plant uptake. The higher PSC has good environmental indications as less P are expected to be lost to the environment (De Bolle, 2013). Thus, recently PSC values have been considered by regulatory authorities as indicators that indicate how likely the nutrients from agricultural fields can be lost to the environment leading to environmental contaminations.

From agricultural perspective, PSC has been incorporated in nutrient management in some parts of the world; as PSC indicates how and how much soil will hold P; thus, it determines the fertilization and management strategies. In soils with low PSC, fertilizer applications are recommended to be applied in split applications to avoid P loss to the environment; for soils with high PSC, fertilizer applications can be applied in single applications or as split applications. For soils with extreme high values of PSC, usually the applied P from fertilizers are held tightly, making it unavailable for plant uptake in that scenarios excess P has to be added to saturate the soil so that extra available P can be made available to plants, however, such practices are costly and not environmental friendly. But also, soil improvement can be done to decrease the strongness of bound P. For example adding SOC is a promising strategy. Changing the pH and the OC molecules bind P but also more easily release it compared to some minerals. In this study, PSC determined were found to vary among land use and sites studied (Table 27). For instance, the general PSC trend based on the  $Al_{M3}$  and  $Fe_{M3}$  concentration, the common P adsorbent in acidic soils, was 5.62 to 34.85 mmol/kg, which was higher in farming areas, i.e., paddy farming areas (5.62 to 34.85 mmol/kg) and maize farming areas (6.30 to 12.60 mmol/kg) than PSC in the conservation areas (7.92 to 18.10 mmol/kg). Based on  $Ca_{M3}$  concentration as a determinant of P sorption in neutral to alkaline soils, PSC estimated (mmol/kg) ranged; paddy farming (2.37 to 62.24, and mean of 22.95), maize farming areas (32.90 to 35.31, and mean of 34.00) whilst conservation areas had PSC of 4.86 to 50.17 mmol/kg and mean value of 22.95 mmol/kg. Higher PSC values based on  $Ca_{M3}$  were reflected by the higher calcium concentration determined in agricultural soils in the study area (Table 27 and 28). A positive correlation ( $P < 0.001$ ,  $R^2 = 0.43$ ) between  $Ca_{M3}$  and  $PSC_{M3}$  was observed, indicating influence of  $Ca_{M3}$  in P sorption and availability in studied soils, significantly better than the correlations between  $Al_{M3}$  ( $P < 0.001$ ,  $R^2 = 0.36$ ) and  $Fe_{M3}$  ( $P < 0.001$ ,  $R^2 = 0.24$ ) with

PSC<sub>M3</sub> in the study area. The ratio of P<sub>M3</sub> (the inherent P extracted by M3 method) and Al<sub>M3</sub> as an alternative to estimate the capacity of the soils to adsorb P because in highly weathered tropical soils, Al is the major P sorbent; in UA the ratio of P<sub>M3</sub> and Al<sub>M3</sub> determined were in a range of 3.32 to 12.35 mmol/kg with higher values in farming areas than in conservation areas (Table 27 and 28).

The spatial distribution of PSC (in mmol/kg) were observed to vary among irrigation schemes in the study area. The observed PSC mean values (in mmol/kg) in each irrigation scheme studied were Mubuyuni (15.75), Igalako (15.17), Mahongole (13.42), Ilaji (14.72), Chimala (12.56), Uturo (11.78), Ihahi (9.82), and Isenyela (9.74) (Table 27). This shows the variation in PSC determinants at different places, which affect P availability and solubility (Gichangi *et al.*, 2008; Gonzalez & Fernandez, 2018). For that reason, soils and locations with low PSC have a significant risk of P loss due to runoff and soil erosion, decreasing the amount of P available for agricultural absorption (De Bolle, 2013). Based on the determined PSC, to achieve better crop growth and higher fertilizer returns and less P loss to the environment, split fertilization application practices are recommended in Usangu agro-ecosystem.

#### **(ii) Phosphate saturation degree (PSD) and P loss**

The PSD is an agro-environmental indicator that indicates quantity of available soil P as well as the amount of additional P that may be applied to the soil for safe storage and availability to plants before excess P begins to leach into surface and ground waters. PSD values can be used to predict P loss from agricultural fields to water reservoirs via runoff, soil erosion, and leaching (De Bolle, 2013; Renneson *et al.*, 2016). The PSD estimated in agricultural soils from Usangu agro-ecosystem were observed to range from 0.01 to 17.6%, with a mean value of 2.83% (Table 27). As an alternate measure of P saturation, the P<sub>M3</sub> to Al<sub>M3</sub> ratio was calculated and found to be in the range of 0.01 to 25.0%, with a mean of 4.01%. In general, the soil in Usangu agro-ecosystem classified to be unsaturated in terms of P (mean PSD<sub>M3</sub> was less than 24%) (De Bolle, 2013). The ratio of Al/Fe and Fe/Al were observed to have a negative and positive correlation to PSD of the soil, respectively, indicating that Al has an important role in determining the P saturation in agricultural soils than Fe, thus increased Al in agricultural soils will increase the capacity of soil to hold P (PSC) thus less saturation. Furthermore, the concentrations of Al and Fe had a significant negative correlation with the PSD of the soil in the research area ( $P < 0.01$ ,  $R^2 = -0.57$  and  $P < 0.01$ ,  $R^2 = -0.42$ , respectively). This is due to the fact that Al and Fe increase the soil's capacity to adsorb P, reducing P saturation. As a result,

soils with high Al and Fe levels have a lower chance of releasing P (P loss) into the environment and can accumulate more P without leading to serious environmental concerns.

For that reason, application of mineral rocks that are rich in Al and Fe has been utilized as a management strategy to prevent P loss from agricultural fields in some parts of the world, such as Belgium; however, the practice might limit the P available for plant uptake due to increased P adsorption and fixations, but also the availability of rock minerals might present another applicability challenge, but application of organic materials to increase OM is a cheap option to reduce P saturation (De Bolle, 2013). The study observed variation in estimated PSD among land use where paddy farming areas had PSD of 0.01 to 17.6%, maize farming areas 5.53 to 15.5%, while conservation areas had PSD of 0.26 to 12.71%. Moreover, the study found that PSD was slightly different among irrigation schemes; furthermore, higher PSD values were reported in Ihahi (17.57%), Mahongole (15.48%), Uturo (6.18%), Igalako (5.72%), Kapunga (5.80%), Mubuyuni (3.75%), Chimala (1.62%), Ilaji (1.52%), and Mabadaga (0.56%) (Table 27 and 29). These values were in line with a determined concentration of  $Al_{M3}$ ,  $Fe_{M3}$ , and  $Ca_{M3}$ , because they determine PSC and are important parameters in the determination of PSD. About five of the 10 irrigation schemes evaluated had higher PSD values (Ihahi (17.57%), Mahongole (15.48 %), Uturo (6.18 %), Igalako (5.72 %), and Kapunga (5.80 %)), indicating a high risk of P loss to water bodies via leaching, surface runoff, and soil erosion. The maximum sorption was determined by considering the concentration of  $Al_{M3}$ ,  $Ca_{M3}$ , and  $Fe_{M3}$  in mmol/kg; the maximum P sorption ranged from 24.3 to 172.4 mmol/kg (Table 27), where all observed values were above determined PSC indicating there is additional capacity of the soil to adsorb more P from fertilizer added, however considerable P loss might be anticipated in some locations.

### **(iii) The correlation of PSC and PSD to crop productivity**

The PSC and PSD influence crop productivity as it determines P availability to plants and losses (Schoumans *et al.*, 2014). Based on the P equilibrium concentrations among soil colloids and soil solution the PSC determines the capacity of the soil to sorb and store P for a long time and release it to the soil solution as needed (Muindi *et al.*, 2015). As a result, soils with low PSC are more likely to lose P to the environment, making P unavailable for plant uptake while also damaging water reservoirs. However, extreme PSC values, on the other hand, can fix all additional P and render it unavailable for plant uptake, while Al and Fe exacerbate the matter (Barrow *et al.*, 2020; Barrow & Debnath, 2020; Guppy *et al.*, 2005). Based on secondary data from the study area conducted by Ngailo *et al.* (2016) and Kadigi *et al.* (2003) in Usangu agro-

ecosystem and in comparison to PSC data of this study, irrigation schemes with higher PSC (mmol/kg) such as Mubuyuni (17.75), Kapunga (16.24), Igalako (15.17), Mahongole (13.42), and Uturo (11.78) were found to be among of the schemes with higher paddy rice productivity per unit area (2.5 to 4.5 tons/ha) (Ngailo *et al.*, 2016), in contrast to schemes like Ihaji, Ihahi, and Mabadaga which had low PSC are reported to have low paddy rice productivity per unit area (<2.5 tons/ha) (Table 25). High PSC values in agricultural soils reduce the risk of P loss from agricultural fields to surface runoff and water bodies due to fact that soils with high PSC bound P firmly to a solid phase and are partially available to soil solution through desorption and pseudo-equilibrium processes, this substantially reduces the risk of P loss via leaching, surface runoffs and through particulates in eroding soils. Henceforward increases available P for agricultural uptakes, thus guaranteeing better and higher yields. A strong correlation ( $R^2 = 0.72$ ) exist between low PSC and high concentration of P in runoffs or drainages from agricultural fields to rivers and other water reservoirs, thus soils with low PSC are likely to influence high loss of P to surface runoffs hence limiting the P available for agricultural uptake and leading to reduced land productivity. This observation is in line with the study conducted by De Bolle (2013) and Vandenest (2015), which reported that Flanders (Belgian) soils with low PSC and high PSD influenced high P loss to water bodies and environment in general and experienced low land productivity compared with soil which had higher PSC and low PSD. The ratio of  $P_{M3}$  to  $Al_{M3}$  and  $Fe_{M3}$  ( $M3$ ), which determines the availability of P for plant uptake determined in this study were 0.00016 to 0.16 (Table 27), which corresponded to below optimum ( $M3 < 0.06$ ) to optimum class ( $M3$  0.06 to 0.11), however, few soils from Ihaji and Mahongole irrigation scheme were observed to have  $M3$  greater than 0.11, which were observed to be above optimum (Mallarino *et al.*, 2013), this means that any P addition in these sites will likely accelerate P loss to surface and groundwater resources, making P fertilization uneconomical while increasing production costs.

#### **(iv) The PSC and PSD as an agro-environmental indicators**

Traditionally, agriculture has long been thought to be both good and bad for the environment (OECD, 2019). Sometimes agriculture has a positive impact on the environment, such as trapping greenhouse gases in crops and soils or reducing flood risks by using specified farming practices. Agriculture, on the one hand, can have a significant negative impact on the environment by contaminating, polluting, and degrading soil, water, and air quality (Moss, 2008). Agriculture, by clearing natural vegetation and substituting natural nutrient cycles and

soil conservation mechanisms, has the potential to destroy natural ecosystems. As a result, agriculture has an impact on the ecosystem in terms of both degradation and sustainability (Vanni *et al.*, 2005). For that reason, every agro-ecosystem assessment should consider both agricultural and environmental factors. PSC and PSD parameters have been developed as agro-environmental indicators for agricultural fertility management, environmental protection, and monitoring. The PSD determines how much additional P loading in the soil can be added before P desorption/nutrient loss rises to an environmental concern, while PSC determines how much P can be added to ensure better P availability for plant uptakes and less loss to the environment (De Bolle, 2013; Kleinman, 2017; Schoumans & Chardon, 2014; Sharpley *et al.*, 2001; Van Meirvenne *et al.*, 2007). The estimated PSD in Usangu agro-ecosystem was less than 24%, suggesting that most areas had unsaturated P status; however, the PSD in Mahongole and Ihahi was high (12.71 to 17.57%), indicating that P loss and eutrophication were likely to occur. The presence of a high PSD in Mahongole and Ihahi suggests that soil has limited additional capacity to securely contain and store additional P. Therefore, that soil will be characterized by high P loss to the environment and low productivity (Wang *et al.*, 2016). Furthermore, the determination of PSD found the potential hotspot which can accelerate the P loss to the environment in the landscape, which otherwise could be difficult to identify; thus agricultural and environmental management measures have to be in place to ensure the effective use of P and less loss of P to the environment. Soils in the study area had PSC ranging from low to high (6.3 to 34.85 mmol/kg) (Table 27), indicating high to low P loss to the environment (Bortoluzzi *et al.*, 2015; Fortune *et al.*, 2005).

For long-term P management in agro-ecosystems, it is critical to determine the PSC and PSD of agricultural soils and use them to estimate the P availability for plant uptake as well as the risk of P loss to water reservoirs which can cause serious water eutrophication and non-point source water pollution. According to the study findings, the estimated PSD<sub>M3</sub> (0.01 to 17.57 %) is low to high, indicating a minimal risk of P loss to the environment. The estimated PSC<sub>M3</sub> and PSD<sub>M3</sub> suggest that, however, soils in the study area have enough capacity to securely store extra P for higher crop output; in some soils had very low PSC and high PSD close to a critical level (25%), which if exceeded could result in serious P loss to the environment; thus, immediate precautionary actions are needed to ensure sustainable P management for increased productivity and reduced environmental contamination. The PSC and PSD determination as agro-environmental indicators in Usangu agro-ecosystem offer a step forward toward starting site-specific P management tactics which will ensure increased land productivity and reduce

potential P loss to the environment. To monitor P concentration and dynamics in farming areas, further spatial-temporal investigations are needed in Usangu agro-ecosystem for achievable high land productivity, environmental safety, and sustainability. Therefore, PSC and PSD can be used simultaneously in agriculture to assure higher fertilizer use efficiency and high productivity, as well as environmental indicators to evaluate the risk of P loss to the environment and its consequences (Gichangi *et al.*, 2008; Kleinman, 2017). This study provides PSC and PSD data that had never been established in Tanzanian agricultural soils before, which can be used in agricultural land use management, particularly for estimating fertilizer requirements for increased land productivity and reduced nutrient loss that leads to environmental contamination.

#### **4.2.4. Sorption and desorption of phosphate in soils of UA**

##### **(i) General soil properties**

In agricultural soils, added plant nutrients such as P from fertilizer and other soil fertility management materials usually interact with soil colloids. The added P might dissolve in soil water and get mixed with soil solution, where it becomes available for plant uptake. Some P is adsorbed or fixed in soil colloid and become less available to plant uptake; the P adsorption usually occurs when concentration of P in soil solution is higher than those in soil colloids. Usually, P in the soil exists as a negatively charged anion; thus, it binds itself to positively charged cations such as  $\text{Fe}^{2+}$ ,  $\text{Al}^{3+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and SOC when adsorbed P in metal cations, its availability is reduced, and the risk of P loss to the environment is reduced by >50% (Shreckhise *et al.*, 2019). The adsorbed P in soil colloids can be released into soil solution, especially when P in soil solution is reduced either by plant uptake or leaching. Thus, availability of P added in agricultural soils for plant uptake, and loss to the environment depends on soil sorption and desorption capacity. The assessment of agricultural soils through batch sorption and desorption experiments generates useful information on how P interacts in agricultural soils and how the added P is likely to be available for plant uptake or lost to the environment. The sorption-desorption experiments are usually conducted by incubating soil samples with different solutions with varying P concentrations and allowing them to equilibrate for 24 hours, then P concentration remaining in solution and that adsorbed in soil colloids is estimated. Despite the importance of this experiment and generated information, best to my knowledge and current information available, this experiment has never been conducted in soils from Usangu agro-ecosystem and almost all Tanzanian soils in the past 30 years. This

study conducted a sorption-desorption batch experiment of 15 composite soil samples from ten irrigation schemes from Usangu agro-ecosystem (Table 29 to 32, Fig. 18).

The P sorption and desorption in agricultural soils of Usangu agro-ecosystem were determined mainly by Fe and Al concentrations, where the studied soils were observed to have  $Fe_{ox}$  (9.45 to 131.54 mmol/kg) and  $Al_{ox}$  (12.19 to 53.28 mmol/kg) (Table 29). The studied soils were observed to have PSC of 16.70 to 79.55 mmol/kg and a PSD of 10-25%, a common range of PSC and PSD in most agricultural soils in Usangu agro-ecosystem. The inherent P ( $P_{ox}$ ), which is already available in soil colloids which influence the interaction of the added P in agricultural soils, were observed to be in the range of 3.24 to 14.76 mmol/kg, while the soil paste pH was observed to be 4.6 to 7.4 a common pH range of agricultural soils found in Usangu agro-ecosystem.

In addition, organic carbon (OC), which have a positive influence on P sorption and desorption from the soil solution and soil colloids, were found to be 7.87 to 32.44 g/kg. Organic matter can influence P sorption by providing additional sorption sites as it contains some positively charged sites, but also can influence P desorption from soil colloids as it provides competition to adsorption sites because they are negatively charged, which may compete with P ions which are usually negatively charged (Guppy *et al.*, 2005). On the other hand, OC complexes Al and Fe thus reduce the P adsorbents in agricultural soils. Therefore, OM or OC addition may both increase P concentration in soil solution, thus providing more P for plant uptake but also may encourage P loss to the environment. The OC or OM may improve physical-chemical soil properties such as water-holding capacity, soil pH, aeration and other soil properties, which promote plant growth and increased utilization of soil P reserves; resulting in shifting of P equilibrium between P pools in the soil, encouraging more P desorption from soil surfaces (Fink *et al.*, 2016). The OM may promote microbial activity in the soil, resulting in more microbial P immobilization, resulting in increased organic P and reduced adsorbed inorganic P concentrations (Borggaard *et al.*, 2005).

## **(ii) Sorption and desorption of P in agricultural soils from UA**

The agricultural soils from ten irrigation schemes from Usangu agro-ecosystem were tested to adsorb added P from phosphatic fertilizer using  $KH_2PO_4$  solution of varying P concentrations from 0 mg/L to 10 mg/L. These was meant to simulate how added fertilizer will react and behave in agricultural soils. The study found that soils from Usangu agro-ecosystem were

adsorbing P from solution linearly from 0 to 5 mg/L which means the concentration of P which remained in soil solution were observed to be low and more P was found to be adsorbed by soil colloids, making it available for plant uptake when needed, and less loss to the environment had to be expected. However, further addition of P (from 5 to 10 mg/L), which is equivalent to more than 5 mg/L or 50 mg/kg or 100 kg/ha, resulted in a dramatic decrease in the proportion of P concentration adsorbed in soil colloids (Table 30, Fig. 18). That means more P were left in the soil solution; this is due to the saturation of the adsorption sites, as the added P were more than the soil colloids can adsorb added P. Despite the fact that the remaining P in soil solution will be easily and free available for plant uptake and nourishing crop growth, but there is a high P loss risk from agricultural soils to water resources and other ecosystems through leaching, surface runoffs, and soil erosion particulates. This indicates that application of fertilizer at a rate equivalent to more than 5 mg/L, 50 mg/kg or 100 kg/ha for most soils in Usangu agro-ecosystem in a single application will not be economical, and higher fertilizer return will not be attained because a large amount of P will be in soil solution and will be likely to be easily lost to the environment. Under such scenario, split-fertilization practices are recommended to guarantee high fertilizer return and reduced P loss to the environment. In all soil samples studied, there was batch experiments where no P were added and resulted in the appreciable P concentration in soil solution; this indicates natural P desorption from inherent P. Soil with high inherent P concentration is potentially a hotspot for P loss and is associated with high P desorption and loss risk to the environment.

The spatial assessment of sorbed and desorbed P among soil from Usangu agro-ecosystem observed that soils from Mubuyuni (MB P2), Ihahi (IH P2), and Igalako (IGA P1) had a higher rate of P desorption from inherent P from soils. Soils from Kapunga (KAP P1, KAP P2, and KAP P3), Ihahi (IH P1), Mahongole (MAH P2), and Chimala (CHI P1) were found to have a higher P sorption rate leaving less P in the soil solution (Table 31 and 32). Generally, soils from Igalako (IGA P2), Ututro (UT P1) and Mubuyuni (MB P2) had higher P adsorption rate (from 0 to 5 mg/L), and less P were observed to remain in soil solution, thus posing less risk of P loss to environment. However, all soils experienced less P adsorption and higher P desorption from 5 mg/L to 10 mg/L allowing more P in soil solution and thus available to plants and high risk of P loss to the environment. This indicates that addition of P fertilizer at a rate of more than 5 mg/L in agricultural soils from Usangu agro-ecosystem in a single fertilization plan will result in serious P loss and thus affecting agricultural productivity and leading to environmental contaminations such as eutrophication of connected water bodies. Furthermore,

soils with higher  $\text{Al}^{3+}$  and  $\text{Fe}^{2+}$  were observed to have higher P sorption and less P desorption, thus posing less risk of P loss to the environment. In that context, there is a possibility to use Al and Fe rich materials as management strategies to ensure more P is available in agricultural soils for increased yields and less P loss to the environment.

#### **4.2.5. Soil quality and earthworm diversity in Usangu agro-ecosystem**

##### **(i) Earthworm species diversity and biomass**

Farming practices have a pronounced influence on availability of soil micro and macro organisms as they are responsible for soil structure and soil chemistry, which are determinants of the availability and activities of soil microbes in the soil (Mcinga *et al.*, 2021). The current paddy rice farming was observed to have an influence on earthworm diversity in agricultural soils. The commonly earthworm species which were found in Usangu agro-ecosystem were endogeic such as *Apporectodea caliginosa* and *Pontoscolex corenthrurus*; these are earthworms that make horizontal barrows and they feed on subsurface organic materials and anecic species such as *Lumbricus terrestris* and *Fimoscolex sporadochaetus*. These are earthworms that feed on surface organic materials and they make vertical barrows improving soil water infiltrations. These are among common earthworm species which are resistant or tolerant to tillage disturbance (Mcinga *et al.*, 2021). It was found that number of earthworms found per meter square in Chimala, Igalako, Ihahi, Kapunga, Mahongole and Uturo were less than 25, a recommended FAO earthworm count per meter square in healthy agricultural soils (Table 33, Fig. 19). This indicates that the current farming practices are not in favour of earthworm availability and diversity. On the other hand, less intensified farming areas or irrigation schemes such as Chang'ombe, Isenyela, and Ukwavile were found to have 25 to 40 earthworms per square meter of agricultural soils. This indicates that natural environment and conservation areas associated with high crop residues and organic manure application and crop diversification encourages earthworm activity and their abundance. The number of earthworms observed per meter square in UA were observed to be lower compared with number of earthworms found in other parts of the world. For instance, the study by Mcinga *et al.* (2021) in semi-arid and humid areas of South Africa found number of earthworm per meter square ranging from 40 to 123, and observed more than 6 type of earthworm species compared with 4 which were observed in UA.

From this study, it is clear that paddy farming intensifications, which is dominated by high use of agrochemicals such as fertilizer and pesticides, and deep ploughing have an interfering role in soil earthworm abundance and diversity, the same scenario was observed by Ayuke *et al.* (2011) and Kiss *et al.* (2021) who reported agricultural management such as fertilizer and pesticides applications, and deep ploughing affected the abundance and diversity of earthworms in tropical agricultural soils across the sub-humid to semi-arid tropical zones of Eastern Africa (Embu, Impala, Nyabeda, and Kabete in Kenya and Chitala in Malawi) and Western Africa (Tamale in Ghana, Ibadan in Nigeria, Sadore in Niger, and Farakoba, Sarias I and III in Burkina Faso). The reduction of earthworms abundance in agro-ecosystem, may reduce the ecosystem functioning such as nutrients recycling due to reduced mineralization which later will cause dependence on inorganic fertilizer for soil fertility to achieve higher land productivity, thus rendering the unsustainability of agro-ecosystem and further increasing environmental contamination which will further severely affect earthworm abundance as supported by Yuvaraj *et al.* (2021). Furthermore, it was found that schemes that are usually under continuous floodings like Kapunga, Ihahi, and Chimala were observed to have low earthworm abundance because most of the time, soils in these schemes are in an anaerobic condition, which is not suitable and favourable to most soil invertebrates diversity, where the same scenario was observed by Kiss *et al.* (2021), who found that continuous flooding were observed to affect earthworm abundance (-59.18%), compared with earthworm abundance in rarely flooded soils across UK fields (Reading, England, and Yorkshire).

The earthworm biomass, which was obtained by determining the fresh weight, oven-dry weight, and ash-free weight of the collected earthworms per square meter, were observed to follow the same trend as of earthworm abundances. Where irrigation schemes like Chang'ombe, Isenyela, Mabadaga, Mubuyuni and Ukwavile were observed to have 40 to 78 g/m<sup>2</sup> earthworm biomass based on ash-free weight (Fig. 19, Table 31), the biomass indicates the earthworm health, soils with well-nourished earthworms and large abundance is likely to be healthy soils, and it will support better plant growth and allow better nutrient recycling and their availability in agro-ecosystem (Abail & Whalen, 2021). The earthworm biomass determined across studied irrigation schemes in Usangu agro-ecosystem was lower than the global average (range of 2 –150 g/m<sup>2</sup>, with a mean of 78 individuals per m<sup>2</sup>). The irrigation scheme with high earthworm abundance and biomass will better support land productivity through nutrient (N and P) recycling, environmental quality, and sustainability of agro-ecosystem due to degradation of organic matter and toxic metals or contaminants.

## **(ii) Species diversity index (H) and specie evenness (E)**

The earthworm diversity index (Shannon index) in the Usangu agro-ecosystem was observed to be limited (ranging from 0.2 to 1.4) (Table 33, Fig. 20). The higher H was observed in Chang'ombe, Isenyela, Ukwavile, and Mabadaga. Based on the determined H, there is little diversity of earthworm in Usangu agro-ecosystem; this might be associated with the current farming practices where those vulnerable earthworm species have been either migrated to other land use or died due to an unfavourable environment in the agro-ecosystem. The earthworm diversity observed in Usangu agro-ecosystem were observed to be lower (0.2 to 1.4) compared with those determined by Mcinga *et al.* (2021) which were observed to be 1.3 to 1.9 in different agricultural soils in Eastern Cape province, South Africa, indicating that deterioration of AE.

The species evenness for earthworms among irrigation schemes in Usangu agro-ecosystem has been observed to range from 0.56 to 0.99 (Table 33, Fig. 20). This indicates that there is a close similarity of the earthworm species across studied irrigation schemes; however, there was no complete evenness of the earthworm species among schemes ( $E < 1$ ). Generally, it was found that earthworms commonly found across all irrigation schemes were almost similar however varied in their abundance and size. The earthworm evenness determined in Usangu agro-ecosystem (0.56 to 0.99) were higher than that determined by Mcinga *et al.* (2021) which were observed to be 0.60 to 0.94 in different agricultural soils in Eastern Cape province, South Africa, that means there few earthworm species found in Usangu agro-ecosystem compared with other agro-ecosystems in the tropics, this might be caused by similarity of farming practices and managements which are implemented in Usangu agro-ecosystems.

It was found that in Usangu agro-ecosystem, the diversity and evenness were much higher in irrigation schemes that are less disturbed and less intensified (Chang'ombe, Isenyela, Mabadaga, Mubuyuni, and Ukwavile) compared with highly disturbed and intensified schemes such as Kapunga, Igalako, Ihahi, Chimala, Uturo, and Mahongole. The less disturbed and intensified schemes not only have a greater number of species present but also the individuals in the community are distributed more equitably among these species, the same scenario determined by Kiss *et al.* (2021) across UK fields. Conclusively, different levels of disturbance have different effects on earthworm occurrence, distribution and diversity. To improve earthworm occurrence and sustain biodiversity in a given area, it is critical to better understand how different management practices affect diversity. Because diversity indices provide more information than just the number of species present (i.e., they describe some species being rare

and others being common), they are valuable tools for quantifying diversity in a community and describing its numerical structure. However, this information was never established in Usangu agro-ecosystem, and the available ones are still at its infancy. Thus, more comprehensive studies employing more techniques and more species consideration are needed to characterize soil invertebrates and microbial communities in Usangu agro-ecosystem.

#### **4.2.6. Potentially toxic elements (PTEs) accumulation in soils, water, and plants in Usangu agro-ecosystem**

##### **(i) Physical and chemical soil properties in study area**

The accumulation, distribution, and bioavailability of PTEs in agricultural soils are derived by many physico-chemical soil factors, such as salinity, soil pH, organic carbon (OC), metal cations, and moisture content. These factors modify the soil condition, thus changing the way PTEs react and interact in the soil. Thus any attempt to study PTEs accumulation, distribution and bioavailability in agricultural soils should take these factors into consideration so that can draw varied conclusive remarks. The essential physical and chemical soil properties of soils from Usangu agro-ecosystem were studied, summarized and presented in Table 34. Where electric conductivity (EC) of soil paste which significantly determines the availability of PTEs were in range of 69.7 to 128.0  $\mu\text{S}/\text{cm}$  with a mean value of 102.23  $\mu\text{S}/\text{cm}$ . Comparatively higher EC values were found in Ilaji, Uturo, and Igalako (196.0, 100.9, and 128.1  $\mu\text{S}/\text{cm}$ ), respectively. The observed EC values (69.7 to 128.0  $\mu\text{S}/\text{cm}$ ) were in a range of medium to high, which could have a profound influence on PTEs and plant nutrients bioavailability. Studies have shown that soils with high EC or salinity are more prone to be affected by PTEs accumulation, and their impacts on soil microbes and plants will be intense. The study by Du Laing *et al.* (2008) and Usman (2015) found that floodwater salinity enhanced the mobility, bioavailability and uptake of Cd by duckweed (*Lemna minor*) which were growing in saline soils; also, the concentration of Cd in pore water in soils and sediments surrounding areas and surface water with high EC significantly exceeded sanitation thresholds and quality standards during flooding. Thus, flooding irrigation type common in paddy farming in Usangu agro-ecosystem, might be enhancing PTEs bioavailability to the environment, surface water, and plants. This implies that risks related to Cd and other PTEs uptake by organisms and Cd leaching to ground water are higher in agricultural soils with higher EC values compared with non-saline soils.

Soil pH significantly influences PTEs solubility and availability via soil acidifications; acidified soils have higher bioavailable PTEs than those near neutral. The pH range found in Usangu agro-ecosystem were in a range of 6.4 to 7.6 which corresponds to slight acidic to slightly alkaline. Because low soil pH increases PTEs diffusion, the pH range observed is likely to influence PTEs solubility and bioavailability in agricultural soils (Qiao *et al.*, 2020).

Organic carbon (OC) is a key factor in the solubility and bioavailability of PTEs; the study found that in most soils from Usangu agro-ecosystem, OC were in the range of 0.37 to 2.37%, where most sites had OC below 2%, a recommended value in agricultural soils. Due to the fact that OC has a higher affinity to PTEs due to alcoholic, carboxyl, carbonyl, and phenolic groups, soils with higher OC have a potential to retain higher PTEs concentration before resulting toxicity effect to soil invertebrates and plants, but also could limit the availability and uptake of PTEs by plants through chelation and complexation (Gujre *et al.*, 2021). Therefore, low OC determined in Usangu agro-ecosystem might increase PTEs bioavailability and plant uptake, thus increasing the risk of PTEs to environmental and human health, to avoid PTEs bioavailability, addition of organic manure or crop residues or any material that will increase organic matter and organic carbon at large is recommended (Usman, 2015). Soil moisture content (MC) helps identify the types of wastes that pollute the soils (dry waste, wet waste, and leachate), but the range of precipitation may also influence MC, which is related to soil texture. The soil moisture content (MC) in the soil of the Usangu agro-ecosystem were observed to be in a range of 2.7% to 7.65%. The availability and dynamics of PTEs in agricultural soils may be influenced by a combination of several physical and chemical soil characteristics, whether directly or indirectly.

#### **(ii) Total PTEs concentrations (*aqua regia* extract)**

Total PTEs in agricultural soils represent the whole portion of PTEs that is potentially available in agricultural soils currently or in the near future; this fraction includes PTEs easily available or extractable PTEs (DPTA or Mehlich 3 extractable) and those available in organic and complexed forms, which traditionally are not available for plant uptake and soil invertebrates which requires strong acid digestion extraction. However, they are likely to be available when soil condition changes, such as in enhanced acidification, salinization, and extreme weathering events. The total PTEs (AQ) concentration in the environment represents the potential risk that will be likely to occur in the particular ecosystem currently and in the near future. The study found that total PTEs concentration in agricultural soils in the Usangu agro-ecosystem among

land use and irrigation schemes were significantly different ( $P < 0.001$ ) among sampling sites, irrigation schemes, and land use (Fig. 21, 22 and 23). The total PTEs mean concentration (in mg/kg) in soils from different land use and irrigation were as follows; Zn (18.25), Cr (1.54), and Co (2.92). The concentration (in  $\mu\text{g}/\text{kg}$ ) of other AQ potentially toxic elements were Sb (27.34), Ag (36.54), Mo (281.88), As (1381.73), Pb (5661.04), Cd (21.49), Hg (3.28), Cu (3342.39), Ni (4106.92), and Se (2695.75). The concentration of PTEs determined when compared with established Tanzania permissible limits in agricultural soils (URT, 2007) to assess the level of contamination was found that some PTEs, i.e., Co, Se, Ag, As, Fe, and Mo were above permissible limits (Table 12). However, when they were compared with USEPA maximum threshold most PTEs were observed to be above the limits. That means their concentration in agricultural soils was higher than the established regulatory value; this might cause a negative impact on soil microbes and invertebrates, plants and humans but also might inhibit the availability of some plant nutrients such as P, which has a higher affinity to metal cations (Wang *et al.*, 2008).

On the other hand, the concentration of Cr, Mn, Cd, Pb, Cu, Zn, Hg, Co, and Mn were observed to be within the established Tanzania maximum allowable limit, indicating that their concentration or their accumulation and distribution in agricultural soils at the current status pose no or less risk to the environment and human health. It was found that among 198 soil samples from ten irrigation schemes studied, about 99.48%, 86.53%, 66.32%, and 11.92% had Fe, As, Se and Hg concentrations exceeded the established permissible limits indicating the presence and enrichment of PTEs contaminants to agro-ecosystem, this might cause potential negative impacts to environmental quality and food safety (Yuvaraj *et al.*, 2021; Zhou *et al.*, 2021). Furthermore, the comparison of determined total PTEs with the regulatory value established by United States Environmental Protection Agency (USEPA) values (Table 12) observed that most of the concentrations of determined PTEs were above the USEPA established permissible limits; this is due to the fact that regulatory values (maximum permissible limits) established vary from one regulatory authority or country to another. Some are very low (thus putting strict control and regulation), while others are very high (thus putting a large range of contamination tolerance and a bit relaxed control and regulations). The Tanzanian maximum permissible limits are higher than those established by USEPA, which means an area can be characterized and classified to be polluted or contaminated by one regulatory authority, and the same area be classified as uncontaminated or unpolluted by other regulatory authority. During this era of intercontinental trade, marketing and collaboration

against environmental and climate change, the lack of unified or harmonized regulatory values or standards is a potential barrier towards environmental safety and sustainability achievement. The total PTEs (AQ-PTEs) concentration (in mg/kg dry wt) among irrigation scheme groups that are between group I, which is usually dominated by farming areas alone, and group II which has farms and scattered settlement areas as described in section 3.1 were observed vary among groups such as Cr (Group I=1662  $\mu\text{g/kg}$  and Group II=1307  $\mu\text{g/kg}$ ); Co (Group I=3.11 mg/kg and Group II=2.62 mg/kg); Zn (Group I=17.47 mg/kg and Group II=19.86 mg/kg); As (Group I =1303.2  $\mu\text{g/kg}$  and Group II=1544.11  $\mu\text{g/kg}$ ); Cd (Group I=18.03  $\mu\text{g/kg}$  and Group II= 29.99  $\mu\text{g/kg}$ ); Cu (Group I=4109.06  $\mu\text{g/kg}$  and Group II=1754.04  $\mu\text{g/kg}$ ); and Pb (Group I =5272.27  $\mu\text{g/kg}$  and Group II=6655.55  $\mu\text{g/kg}$ ). The study found that concentration of PTEs generally was higher in irrigation schemes that had farms alone (group I) compared with schemes that had farms and scattered settlements (group II); this might be influenced by the level of agricultural intensification and associated anthropogenic activities in these areas compared with group II schemes. Therefore, to avoid additional increases in PTEs in agricultural soils, management practices must be implemented.

The comparison of PTEs determined in Usangu agro-ecosystem, and other parts of the world observed that, total PTEs determined in Usangu agro-ecosystem were lower than values reported and determined in other parts of the world; for instance, the concentration of Pb (5.27 mg/kg) and Zn (18.249 mg/kg) determined in Usangu agro-ecosystem were lower than those determined by Abdullahi *et al.* (2014) in topsoils in Birnin Gwari in Nigeria (Zn=61.82 mg/kg and Pb=20.83 mg/kg) and determined total Cd, Cu, Pb, and Ni were lower compared with values reported by Shah *et al.* (2013) in Pakistan. Despite the fact that this indicates the studied agro-ecosystem is less polluted, the future situation is not guaranteed and might change in the near future due to increasing agricultural intensification, industrialization, and urbanization in the area.

### **(iii) Land use influence on total PTEs concentrations (*aqua regia* extracts)**

Naturally, soil and the environment, in general, contain some traces of PTEs from geological origins, however, they are available in small amounts and they are concentrated in few areas, and they are not spatially distributed. Thus, any higher PTEs values in the environment, including in agricultural soils, water, and sediments, are highly influenced by anthropogenic activities such as the use of agrochemicals in farming, wastewater use in irrigation, urban and industrial effluents. This study characterized the PTEs distribution in three land use, where a

strong correlation of land use with PTEs accumulation among land use was observed, where significantly high PTEs concentrations ( $P < 0.05$ ) were determined in maize and paddy farming areas than in conservation areas (Table 35 and 36, Fig. 21) as a result of farming practices and intensifications. This indicates that land use highly influences PTEs accumulation status and its distribution in agro-ecosystem. Among farming areas, paddy rice farming areas (in group II) were observed to have significantly higher PTEs accumulation ( $P < 0.05$ ) than maize farming areas, this may be due to agricultural intensification observed in paddy farming areas which involve high use of fertilizer, herbicides, and pesticides and location of paddy farming areas which usually located in the lowlands, compared with maize which is usually cultivated in undulating slopes. The total mean values (in mg/kg dry wt) of some PTEs in three land-use were; Cr in paddy (15.31), maize (13.34), and conservation area (11.89); Cd in paddy (21.06), maize (31.86), and conservation areas (17.98); and Pb in paddy farming (6.578 mg/kg), maize farming (6.324 mg/kg), and conservation areas (6.039 mg/kg). PTEs concentrations in different land-use based on scheme classification (Group I and II) were statistically significant different, whereas group II in conservation areas had higher PTEs concentrations. While group I and group II in maize and paddy farming areas had higher PTEs concentrations (Table 35 and 36). The observed pattern indicates that rising PTEs in agricultural areas are mostly due to farming operations and related activities occurring in farming areas or nearby (Moss, 2008; Tutic *et al.*, 2015). Thus any attempt to control and manage PTEs in agricultural soils should be participatory, looking beyond farming areas in the agro-ecosystem.

Over the entire land use, “group I had statistically higher Ni, Ag, Cr, As, Cu, and Co, but group II schemes had higher Se, Mo, Cd, Hg, and Pb concentration (Table 36). Some elements (As and Cr) were observed to be higher in conservation areas than in maize farming areas. This indicates that higher PTEs values could be impacted by wind deposition, vehicular emissions, farming machine leakages, or runoff from nearby towns, which end up in conservation areas rather than farming activities. The same scenario was reported in Luanda Angola (Ferreira-Baptista & De Miguel, 2005) and Spain (Ordóñez *et al.*, 2003), where the underlying geology was not enriched with metals, and substantial PTEs concentrations were identified in restricted or conserved areas demonstrating that PTEs might come from a variety of sources and transported as dust, aerosols, and runoffs to the area. Higher PTEs in conserved areas determined in Usangu agro-ecosystem could possibly be due to natural sources; however, geological materials in Usangu agro-ecosystem are not enriched with PTEs found thus the

possible reason is likely to be other sources such as vehicular emission, dust, aerosols, and surface water runoffs from urban areas” (Delvaux & Hanon, 1993).

The ratio of total PTEs (AQ) by TZ or USEPA maximum allowed limits for PTEs in agricultural soils were estimated to evaluate the contamination and pollution hierarchy (Appendix 5 and 6). The ratio indicates which areas have high exceedance of PTEs from the established threshold but also indicates the likelihood of adverse effects on the environment and inhabitants. The higher ratio indicates high environmental and health risks, and immediate actions are needed to be in place to avoid further accumulation and their environmental and health risk and associated impacts. Based on the calculated contamination/pollution hierarchy, the ratio of Ag, Cr, Mn, Cu, Pb, Co, Zn, Fe, As, and Mo exceeded USEPA maximum permissible limits, showing that AQ:USEPA ratio was greater than one. Out of 198 soil samples studied, 99.48%, 99.34%, 99.42%, 96.67%, 67.68%, and 96.97% of Cr, Pb, Mn, As, Zn, and Cu, respectively, exceeded the USEPA maximum permissible limit for PTEs in agricultural soils. The AQ:TZ ratio as a contamination/pollution hierarchy shows that Co, As, Ag, Mo, and Fe concentrations (Appendix 7 and 8) were above Tanzania's permissible limits (URT, 2007). Higher PTEs in agricultural soils exceeding the permissible limits present environmental and health risks to animals and humans since some PTEs, i.e., Cd, Ni, and Hg are toxic and carcinogenic (Okoro *et al.*, 2020; Sall *et al.*, 2020; Tang *et al.*, 2021). Based on the pollution hierarchy computed, farming areas were observed to have more contamination or pollution risk compared with reserved areas.

#### **(iv) Spatial total PTEs distribution among Usangu agro-ecosystem**

The assessment of PTEs spatial distribution in Usangu agro-ecosystem in all scheme groups (Group I and II) were observed to be significantly variable ( $P < 0.001$ ) among groups and irrigation schemes. It was observed that schemes in lowland (B and C in Fig. 9) had higher PTEs concentrations ( $P < 0.001$ ), such as Cu, Pb, Fe, Co, Ni, Cr, and Al than their counterparts (Table 35 and 36). But also, schemes situated near urban or peri-urban areas (D and E in group II in Fig. 9) had significant higher soil PTEs values such as Ag, Mn, Zn, As, Mo, Cd, Se, and Hg concentration (Table 36). This could be aggravated by runoffs, effluents, and emissions from urban areas and domestic wastes, as supported by Shemdoe (2010) that farming areas that are closer to urban, industrial, and residential areas have higher potential risk of PTEs accumulation which are coming out of the agro-ecosystem itself. The same scenario was observed by Mahugija and Sheikh (2018) in Zanzibar, where farming areas near metallurgical

workshops were reported to contain more Zn, Cd, and Cu concentrations than those areas which were located far from metal workshops. This exemplifies that increasing industrialization and urbanization in and near farming areas might influence the productivity and sustainability of agro-ecosystem, thus any effort made to ensure agro-ecosystem productivity and sustainability must consider also areas which are considered to be out of the agro-ecosystem since their impacts influence agro-ecosystem too.

The comparison of PTEs among irrigation schemes observed that Group I schemes (Mubuyuni, Ilaji, Kapunga, Uturo, and Mabadaga) had a significantly higher Al, Ni, Cr, Co, Fe, Cu, and Pb concentration whilst Group II schemes (Mahongole, Ihahi, Chimala, and Igalako) were observed to have higher Mn, Mo, Zn, Cd, Ag, Se, As, and Hg concentration (Table 36, Fig. 22 and 23). Based on Tanzania PTEs maximum permissible limit in soils (Table 12), “all irrigation schemes had PTEs concentration within permissible limits except for Mo, As, Fe, Co, and Ag which were above the limits. The comparison of total PTEs concentration determined with USEPA values showed that all ten irrigation schemes studied (Group I and II) had a concentration of As, Cr, Zn, Co, Cd, Fe, Cu, Mn, Ag, Mo, and Pb above the limits. The contamination or pollution hierarchy (AQ:TZ and AQ:USEPA) of studied PTEs varied significantly among schemes where the order in decreasing range was Mabadaga > Chimala > Uturo > Mubuyuni > Mahongole > Ilaji > Kapunga > Igalako > Ihahi > Isenyela (Appendix 7 and 8). The concentration distribution maps of different PTEs varied among elements and schemes in the study site, as shown in Fig. 22 and 23, and Appendix 15 shows the spatial variability of PTEs in agricultural soils in Usangu agro-ecosystem, where the concentration of PTEs were observed to increase along the toposequence or landscape gradient” (Mng’ong’o *et al.*, 2021). Based on AQ:TZ computed ratio, most schemes were less polluted with metals and metalloids; however, AQ:USEPA shows that most schemes had PTEs in a pollution state; this might call for harmonization of PTEs regulatory values to have universal PTEs regulatory values which will accelerate joint effort on management and monitoring of agro-ecosystem quality and sustainability despite its potential challenges.

#### **(v) The bioavailable PTEs concentrations (M3 extracts) in Usangu agro-ecosystem**

The determination of total PTEs available in the environment such as in soils, water, and plants tissues is not enough to estimate the exact potential risk which can be inflicted by particular PTEs because total PTEs concentration includes all potential fractions of PTEs available in the environment and other fractions are not easily available for plants, soil invertebrates, and

microbes. Thus, determination of bioavailable PTEs concentration is important because this shows PTEs fractions which is easily available for plant uptake and soil macro and microbes and which can be easily transported from one ecosystem to another. Many regulatory values in many countries are developed based on total PTEs concentrations; this usually causes an overestimation of the risk, which can be resulted from PTEs accumulated. Thus this study characterized bioavailable PTEs in agricultural soils to get a clear picture of PTEs accumulation and distribution in agro-ecosystem and possible environmental and health risks. The determined bioavailable PTEs concentrations were observed to vary significantly between irrigation scheme group I and group II areas. For example, **Co** (Group I=0.83 mg/kg and Group II= 0.49 mg/kg); **Cu** (Group I= 2510 µg/kg and Group II= 810 µg/kg); **Cr** (Group I=55.04 µg/kg and Group II= 19.21 µg/kg); **Zn** (Group I=1.99 mg/kg and Group II 3.09 mg/kg); and **Cd** (Group I=19.22 µg/kg and Group II= 36.82 µg/kg) (Table 36). Total PTEs concentrations in soil (e.g., Cd and Pb) were generally lower in Group I locations compared with Group II areas, with the exception of Cu. When compared with the results obtained after acid digestion (AQ), the bioavailable PTEs were substantially lower. The determined levels, however, are high enough to alter the availability and uptake of plant nutrients such as P, as well as cause pollution and contamination in the environment.

The ratio of M3 and AQ (M3:AQ) to estimate per cent of PTEs bioavailable for plant uptake ranged 0.3 to 100% among studied PTEs (Table 35 and Appendix 10). Higher bioavailable PTEs cause high health risks since increased PTEs uptake by plants contaminates food and water, posing a health risk when consumed by animals and humans (Agrelli *et al.*, 2017; Atafar *et al.*, 2010; Fagnano *et al.*, 2020; Ordóñez *et al.*, 2003; Visconti *et al.*, 2019). It was found that the bioavailable PTEs distribution in different irrigation schemes and land use were significant different from one land use and another or from one scheme to another, however, they were observed to follow the same trend as displayed by total PTEs (AQ) concentration in agricultural soils as described in Section 4.2.6 (iv). This might be influenced by agrochemicals application and runoffs from the semi-urbanized settlement and signifies that increased total PTEs in agricultural soils will increase PTEs availability and bioavailable, which can be easily taken up by plants and soil macro and microbes thus potentially affecting their health (Nriagu, 1992).

#### **(vi) Bioavailable PTEs spatial distribution among irrigation schemes and land use**

The bioavailable PTEs spatial distribution among land use and land groups were shown to be significantly higher in farming areas (in paddy farming and maize farming areas) ( $P < 0.05$ ) than

in conservation areas (Table 35). Land use group I had a higher bioavailable Co, Al, Cr, Cu, Fe, and Ni concentrations, while group II had a higher Ag, Mn, Cd, Pb, Mo, Zn, As, Hg, and Se concentration (Table 35). The concentration of some bioavailable PTEs studied among land-use were; **Pb** in paddy farming (Group I=1.87 and Group II=1.65 mg/kg), maize farming (Group II=1.87 mg/kg), and conservation areas (Group I=1.82 and Group II=2.02 mg/kg); **As** in paddy farming (Group I=190 and Group II=270 µg/kg), maize farming (Group II=170 µg/kg), and conservation area (Group I=187 and Group II=161 µg/kg); **Cd** paddy farming (Group I=19 and Group II=38 µg/kg), maize farming (Group II=33 µg/kg), and conservation area (Group I=17 and Group II=36 µg/kg) (Table 35).

The comparison of the ratio of bioavailable and total PTEs concentration (M3:AQ) in different land use was significantly different among PTEs, where higher values were observed for Ag (11-100%), Cu (48-64%), Cd (0-100%), Mn (33-61.3%), Se (43-74%), and Pb (25-38%) (Appendix 9 and 10). The high bioavailable PTEs increase PTEs uptake by plants leading to food and fodder contamination; it is evident that agricultural soils enriched with PTEs are likely to produce crops with elevated levels of PTEs, thus leading to health risks (Teng *et al.*, 2010).

Bioavailable PTEs distribution significantly varied across schemes (Appendix 9 and 10), where schemes in group I observed to have higher concentration (µg/kg) of Pb (640-2740), Cu (300-4200), Co (291-1619), As (86-468), Ni (93.281-1770), and Ag (0.2-33.12) while schemes in Group II had higher concentration (µg/kg) of Cd (18.3-39.3), Hg (0-0.35), Zn (2500-3400), Cr (13.5-101.5), and Se (0-2470.7) (Appendix 9). Based on the M3:AQ ratio, higher PTEs bioavailability detected in Mn (Group I =27-81% and Group II= 42-67%), As (Group I =7-45% and Group II=2-18%), Cd (Group I = 4-100% and Group II=4-100%), and Cu (Group I=12-44% and Group II=40-54%) (Appendix 10 and 12), where group I schemes were observed to have a higher concentration of bioavailable PTEs than group II, this indicates that all these schemes could increase PTEs availability to agricultural soils and later to plant tissues and fodders, and intensified farming areas might be a major cause of increased PTEs in agro-ecosystem.

#### **(vii) PTEs evaluation by pollution and contamination indexes**

The increasing PTEs concentration in agro-ecosystem have environmental and ecological impacts when available in elevated levels. The determination of PTEs concentration in agricultural soils and sediments and comparing them to regulatory values can be used as a

simple environmental assessment indicator (URT, 2007). In this study concentration of PTEs determined were compared with maximum permissible limits developed by national and international regulatory authorities to evaluate contamination and pollution status as described in Section 4.2.6 (i to vi). Furthermore, for detailed characterization, the risk of PTEs accumulation in agro-ecosystem can be estimated by using the internationally established contamination and pollution indexes to provide needed information for early management warnings (Li *et al.*, 2019). The evaluation of PTEs contamination and pollution in Usangu agro-ecosystem were further conducted. The indexes studied were based on total PTEs among land use and irrigation schemes were; adverse effect index (AEI), geochemical accumulation index ( $I_{geo}$ ), contamination factor (CF) and pollution load index (PLI), enrichment factor (EF), potential ecological risk index ( $E_r^i$ ) and comprehensive risk index (RI). The determined index values presented in Table 37 to 49 and their description and interpretation are as follows:

**(a) Geochemical accumulation index ( $I_{geo}$ )**

This index is used to assess the degree of PTEs contamination in agricultural soils or sediments in agro-ecosystems (Equation 10). The  $I_{geo}$  compares the PTEs concentration in the studied soils with respect to the background material in the area while including the possible lithological changes (Gashi *et al.*, 2017; Kersten & Forstner, 1986; Malsiu *et al.*, 2020; Suresh *et al.*, 2011). From the general and established class of  $I_{geo}$ , “the interpretation of the obtained  $I_{geo}$  values are as follows:  $I_{geo} \leq 0$ , unpolluted;  $0 \leq I_{geo} \leq 1$ , unpolluted to moderately polluted;  $1 \leq I_{geo} \leq 2$ , moderately polluted;  $2 \leq I_{geo} \leq 3$ , moderately to heavily polluted;  $3 \leq I_{geo} \leq 4$ , heavily polluted;  $4 \leq I_{geo} \leq 5$ , heavily to extremely polluted; and  $5 \geq I_{geo}$ , extremely polluted” (Malsiu *et al.*, 2020). From Usangu agro-ecosystem, the  $I_{geo}$  values determined for different PTEs were significantly different (Table 39 and 40) where  $I_{geo}$  values for some PTEs studied among land use were; in conservation areas ((Cr (0.10 to 0.11), Co (0.19 to 0.30), Zn (0.10 to 0.11), Ag (0.08 to 0.15), As (0.04 to 0.041), Cd (0.09 to 0.11), Cu (0.15 to 0.21), Hg (-0.35 to -0.15), Ni (0.14 to 0.19), Pb (0.15 to 0.17)), in maize farming area (Cr (0.1 to 0.12), Zn (0.10 to 0.11), Ag (0.09 to 0.14), As (0.04 to 0.043), Cu (0.21 to 0.25), Hg (-0.28 to -0.18), Ni (0.18 to 0.22), and Pb (0.14 to 0.17)), and in paddy farming areas (Cr (0.09 to 0.13), Zn (0.10 to 0.12), Ag (0.08 to 0.17), As (0.04 to 0.05), Cd (0.08 to 0.11), Cu (0.14 to 0.43), Hg (-0.39 to -0.15), Ni (0.12 to 0.36), and Pb (0.12 to 0.21)). It was found that  $I_{geo}$  values determined among three land use for PTEs studied were in a range of 0.06 to less than 2 except for Hg and Mo

indicating all land uses had Uncontaminated (UC) to moderately contaminated or polluted status (UMC) with respect to studied PTEs. Thus, less environmental fate is expected.

Furthermore, it was observed that  $I_{geo}$  values for Hg and Mo were below zero ( $I_{geo} < 0$ ) in all land use and schemes, indicating uncontaminated or unpolluted status; thus, no environmental fate is expected at the current state of Hg and Mo. The same trend and observation were found among irrigation schemes (Table 40), where all computed  $I_{geo}$  values ranged from 0.06 to 0.43, indicating uncontaminated to moderately contaminated status. Scheme such as Isenyela, Ihahi, Igalako, Ilaji, Uturo, Mahongole, Kapunga, and Mubuyuni were observed to have higher  $I_{geo}$  values for Cr, Co, Cd, Cu, Ni, and Pb. Despite the fact that the determined  $I_{geo}$  values were less than 1, there are traces of PTEs contamination or pollution in the studied schemes in Usangu agro-ecosystem. Thus it is important to initiate measures that will ensure PTEs accumulation in agro-ecosystem and nearby areas remains within acceptable limits to ensure high land productivity, environmental quality, and agro-ecosystem sustainability. The limited studies on geoaccumulation in agro-ecosystem in East Africa limited its comparison beyond study area, however, the determined  $I_{geo}$  values were observed to be lower than those determined in river Mara sediments by Nkinda *et al.* (2020) where  $I_{geo}$  determined in UA were found to be below one, indicating that majority of the studied areas were unpolluted or had low pollution risks by PTEs.

#### **(b) Adverse effect index (AEI)**

The AEI compares the total PTEs determined to soil quality guideline values (SQGs). In other words, AEI is the ratio of determined PTEs concentration divided by the maximum allowable limits established by regulatory authorities. The SQGs used to compute AEI in this study were obtained from Tanzania environmental management regulation (URT, 2007). The determined AEI for some PTEs were greater than 1 ( $AEI > 1$ ), indicating that PTEs concentration in agricultural soils exceeded SQGs. Thus, negative environmental and ecological impacts are expected (Uddin *et al.*, 2021). The AEI estimated in Usangu agro-ecosystem among three land use (conservation areas, maize and paddy farming areas) and schemes were observed to be variable among land use and irrigation schemes (Table 37 and 38), where AEI among land use were; in conservation areas (Cr (0.1 to 0.23), Co (1.51 to 5.44), Fe (999.24 to 2108.37), Zn (0.11 to 0.16), Ag (3.46 to 164.26), As (1.02 to 2.91), Cd (0.01 to 0.04), Cu (0.01 to 0.03), Hg (0.00 to 0.01), Mo (58.53 to 603.60), and Pb (0.02 to 0.04)), in maize farming areas (Cr (0.10 to 0.23), Co (1.20 to 4.12), Fe (1069.89 to 1730.33), Zn (0.10 to 0.16), Ag (4.74 to 51.08), As

(1.11 to 1.74), Cd (0.02 to 0.07), Cu (0.01 to 0.011), Hg (<0.001), Mo (373.93 to 581.31), and Pb (0.02 to 0.06)), in paddy farming areas the determined AEI were (Cr (0.04 to 0.19), Co (0.50 to 7.95), Fe (698.95 to 2518.80), Zn (0.04 to 0.43), Ag (1.78 to 218.39), As (0.57 to 2.30), Cd (0.01 to 0.06), Cu (0.00 to 0.05), Hg (0.001 to 0.01), Pb (0.01 to 0.09). The AEI determined among land use were less than 1 (AEI<1) for Cr, Mn, Zn, Cd, Cu, Hg, Ni, Pb, and Se, indicating that PTEs concentration in the soil is not high enough to cause adverse effect to soil biota, i.e., plants, soil microbes, and soil invertebrates. In addition, it was observed that AEI values for Fe, Ag, As, Co and Mo were above 1 (AEI>1), indicating PTEs concentration available in soils could produce adverse effects on plants and soil-dwelling organisms such as earthworms, termites, and ants. On the other hand, the study found very high AEI values for Fe (698.95 to 2518.80) and Mo (7.55 to 814.55). This concentration is likely to be associated with geological materials than anthropogenic contamination. However, additional detailed characterization studies are needed to come up with a clear and conclusive statement.

The AEI spatial distribution among irrigation schemes (Table 37) were observed to follow same general trend pattern as in land-use types whereby in all schemes, their AEI for Cr, Mn, Zn, Cd, Cu, Hg, Ni, Pb, and Se were less than 1 (AEI<1) indicating that PTEs concentration in soil is not high enough to cause adverse effect to soil biota and plants. However, the AEI for Co, Fe, Ag, As, and Mo in all schemes were greater than 1 (AEI>1), depicting that the concentration of these elements in agricultural soils could potentially cause adverse effects to soil inhabitants. The study found that irrigation schemes such as Mabadaga, Chimala, Mubuyuni, Uturo, and Mahongole had higher AEI values (Table 37). This might be influenced by its location as these schemes are located along TAZAM highway and TAZARA railway line, which might be influencing the PTEs due to automobile emissions from cars, trains, etc, as supported by Malunguja *et al.* (2022). But also they are located in the area which allows accumulation of surfaces water runoffs from the city of Mbeya and its growing towns along TAZAM highway and TAZARA railway line; thus management measures have to be in place to monitor and manage the accumulation and distribution of PTEs in agro-ecosystem.

### **(c) Contamination factor (CF) and pollution load index (PLI)**

The CF and PLI are significant because they are used to assess the contamination of PTEs. A CF value of less than 1 indicates low pollution, a CF value of 1 to 3 indicates moderate pollution, a CF value of 3 to 6 indicates high pollution, and a CF value of more than 6 indicates extremely high pollution as described in Table 14 (Gashi *et al.*, 2017; Senkondo *et al.*, 2014).

The CF values determined from Usangu agro-ecosystem among land use and irrigation schemes were observed to vary among land use and irrigation schemes (Table 41 and 42). Where farming areas were observed to have higher CF values (Table 42) compared with conservation areas. CF values for PTEs such as Cr, Co, Mn, Zn, Ag, As, Cd, Cu, Hg, Mo, Ni, Pb, and Se were observed to be less than 1 ( $CF < 1$ ), indicating low pollution of agro-ecosystem. Thus, low negative environmental and ecological impacts are anticipated. On the other hand, the CF values for Al, Fe, and Mg were observed to be greater than 6 (Table 42), indicating that the concentration of these elements in soils in agro-ecosystem was very high that might lead to negative impacts in agro-ecosystem. The values might be influenced by geological materials in the area rather than anthropogenic activities because conservation areas, paddy rice and maize farming areas contained almost similar Fe, Al, and Mg concentration and CF values. High concentration and CF values for Al, Fe, and Mg can badly affect soil pH, an important variable in plant nutrient availability and land productivity in the area. But also high concentrations Fe and Al are likely to influence the availability of toxic metals and inhibit plant nutrient availability such as P, N, S, and K.

The CF values among studied irrigation schemes in Usangu agro-ecosystem were found to vary across schemes, where CF values for Mn, Cr, Zn, Cd, As, Cu, Hg, Mo, Co, Ni, Pb, and Se was less than 1 (0.03 to 0.64) while the CF value for Al, Fe, Mg and Ag for some schemes such as Chimala and Ilaji were greater than 1 ( $CF > 1$ ), showing moderate soil chemical disturbance in agro-ecosystem. Schemes such as Chimala, Isenyela, Mabadaga, Mahongole, Mubuyuni, Uturo, and Ihahi were observed to have more higher CF values indicating more chemical disturbance by most PTEs; this might threaten the productivity of agro-ecosystem affecting achievement of sustainable development goals (SDGs) such as Zero Hunger, Life on Land, and Life below water. The current study was in line with the study by Nkinda *et al.* (2020), who found that CF in river sediments in Mara region were below one ( $CF < 1$ ) in the dry period (months), demonstrating low contamination level while during the wet season, CF determined were between 1 and 3 indicating a moderate degree of PTEs contamination.

Determination of pollution load index (PLI) among land use and schemes in Usangu agro-ecosystem were observed to vary significantly (Table 43 and 44). Where generally, the farming areas were observed to have a wide range of PLI values, such as in maize farming areas (0.62 to 1.14) and paddy rice farming areas (0.40 to 1.30) compared with conservation areas (0.74 to 1.27). The determined PLI values indicate that the site quality in Usangu agro-ecosystem is in

the range of perfect quality (PLI<1) to deterioration (PLI>1) of the site quality. That means there are areas in Usangu agro-ecosystem that still have good quality, but also there are areas in Usangu agro-ecosystem which its quality is deteriorating, and most areas under deterioration status are observed to be in farming areas than their counterparts.

Among irrigation schemes, the PLI was observed to range from 0.48 to 1.16, where schemes such as Chimala, Mabadaga, and Mahongole had PLI>1, indicating site quality deterioration, while PLI values for Igalako, Ihahi, Ilaji, Isenyela, Kapunga, Mubuyuni, and Uturo were less than 1 (PLI<1) (Table 44) indicating perfect quality or no pollution. Despite the fact that in many schemes in Usangu agro-ecosystem, the PLI values were less than 1, but many were very close to 1, indicating that if the situation has to continue at the same current trends, their quality will soon shift to baseline pollutions status. The order of decreasing PLI among schemes were Mabadaga > Chimala > Mahongole > Uturo > Ilaji > Kapunga > Mubuyuni > Ihahi > Igalako > Isenyela. This trend was observed to be in line with agricultural intensification and urbanization in the area. Thus, anthropogenic activities conducted in agro-ecosystem and nearby areas might be responsible for higher PLI values in Usangu agro-ecosystems. Thus, monitoring and management measures to ensure PLI for PTEs studied remain below 1 for better land productivity and agro-ecosystem sustainability has to be in place.

#### **(d) Potential ecological risk index ( $E_r^i$ )**

From the Usangu agro-ecosystem, the  $E_r^i$  determined varied between land use and irrigation schemes. Generally, the farming areas were observed to have larger  $E_r^i$  values than conservation areas for most studied PTEs (Table 45). Across all land use,  $E_r^i$  values for Zn, Cr, Co, Ag, Cd, Cu, Hg, Ni, As, Pb, and Se were less than 40 ( $E_r^i < 40$ ), indicating a low risk of these PTEs in agro-ecosystem. The study found that  $E_r^i$  values for Al, Fe, and Mg were above 320 ( $E_r^i > 320$ ), indicating that high ecological risk can be exerted by these PTEs in agro-ecosystem. Among the farming areas, it was observed that paddy farming areas had higher  $E_r^i$  (0.28 to 29.80), while in maize farming areas had  $E_r^i$  in the range of 0.28 to 15.05 for most PTEs. This indicates that paddy farming areas might be at higher ecological risks than maize farming areas, this might be associated with increased use of agrochemicals in paddy farming than in maize farming; but also the use of surface runoff water for irrigation in paddy farming areas might be a contributing factor because these water runoffs some are originating from industrial and urbanized areas which may rise PTEs levels and plant nutrients as were determined in previous studies (FBD,

2007; Fox, 2004). The determination of  $E_r^i$  among irrigation schemes in Usangu agro-ecosystem were in a range of 0.10 to 52.34 for all schemes and for all 14 studied PTEs except for Al, Fe and Mg, which recorded  $E_r^i$  values of greater than 52 ( $E_r^i > 52$ ). The order of  $E_r^i$  among schemes were Ilaji > Chimala > Kapunga > Mahongole > Ihahi > Mubuyuni > Uturo > Igalako > Isenyela > Mabadaga (Table 45 and 46). Based on the determined  $E_r^i$  values indicate that Usangu agro-ecosystem is at low ecological risk (where  $E_r^i < 40$ ) to moderately ecological risks (where  $40 \leq E_r^i < 80$ ). Thus, intentional management measures have to be in place to control the rise of anticipated ecological risks.

#### **(e) Comprehensive ecological risk index (RI)**

The RI show the toxicity of the PTEs to organisms in soils or sediments, whether high, low or moderate, as shown in Table 9 and 13. The comprehensive risk index computed in Usangu agro-ecosystem (Table 47) were observed to vary among PTEs where the determined values were as follows; Al (7489474), Cr (87.51), Co (2234.24), Fe (6102892.52), Mg (3402645.63), Mn (83.62), Zn (50.90), Ag (5606.11), As (207.60), Cd (1228.89), Cu (142.18), Hg (1249.28), Mo (1436.76), Ni (126.88), Pb (257.44), and Se (410.25). It was found that Cr, Co, Mn, Zn, As, Cu, Ni, Pb, and Se had RI values of less than 600 indicating that their ecological risk in agro-ecosystem was low to considerable risks (Uddin *et al.*, 2021). On the other hand, Al, Fe, Mg, Hg, and Mo had RI greater than 600, indicating that they can potentially cause considerable risks to the agro-ecosystem and environment if continued unmanaged.

#### **(f) Enrichment Factor (EF)**

The EF of PTEs are usually used to evaluate anthropogenic contamination. Where in this study iron (Fe) was selected as a normalizing element (due to its abundance in the study area) for identifying anomalous PTEs contributions (Vemic *et al.*, 2014). Generally, EF is classified into 4 classes which are as follows: “<2, minimal; 2 to 5, moderate; 5 to 20, significant; 20 to 40, very high; and >40, extremely high enrichment” (Nkinda *et al.*, 2020). The assessment of enrichment factor for different PTEs in Usangu agro-ecosystem was observed to vary among land use (Table 48) and irrigation schemes (Table 47). The EF determined among land use for some PTEs were both less than 1 such as in conservation areas ((Cr (0.003), Zn (0.0001), As (0.001), Cd (0.0001), Cu (0.001), Ni (0.001), Pb (0.0001)); in maize farming areas (Cr (0.005), Zn (0.0002), As (0.0001), Cd (0.0002), Cu (0.0003), Ni (0.00002), and Pb (0.0002)); and in paddy rice farming areas (Cr (0.003), Zn (0.0001), As (0.0001), Cd (0.0001), Cu (0.007), Ni

(0.0001), and Pb (0.0001)). All of the determined EF for all 14 PTEs their values were below 2 ( $EF < 2$ ), indicating minimal PTEs enrichment in agro-ecosystem. Furthermore, the study found that EF from farming areas (maize and paddy rice farming areas) were higher than those obtained in conservation areas. This implies that anthropogenic activities such as farming and associated activities may be responsible for higher PTEs enrichment factor observed in farming areas in Usangu agro-ecosystem.

The EF spatial distribution among irrigation schemes was observed to vary among schemes, where, all schemes recorded an EF of less than 2. This indicates that PTEs enrichment was less than 2%; however, this must not be taken for granted or ignored because the effect of PTEs enrichment is serious and hard to reverse. Among PTEs studied, Al, Mg, Cr, Mn, and Cu were observed to have higher enrichment factors values which might be exacerbated by the uses of agrochemicals associated with these PTEs, such as Cu-based agrochemicals. Among irrigation schemes, the order of PTEs enrichment factors in decreasing order was Chimala > Igalako > Ihahi > Ilaji > Isenyela > Kapunga > Mabadaga > Mahongole > Mubuyuni > Uturo. The high EF might be influenced by a number of factors which are both within and outside farming areas due to the nature of farming in the Usangu basin. Studies by Malunguja and Devi (2022) have shown that farming areas and forests located along the highway and diesel-powered trains experienced a huge accumulation of PTEs from motor vehicle emissions due to burning of fossil fuels, which could be a possible scenario for Usangu agro-ecosystem due to its nature and location as it is along the TAZAM highway and TAZARA diesel-powered railway line.

Conclusively, management of PTEs accumulation and distribution in Usangu agro-ecosystem to be achieved requires effort which goes beyond control and management of PTEs just in agro-ecosystem. Thus, to establish or predict productivity, environmental quality, safety and sustainability of Usangu agro-ecosystem might need a holistic and integrative approach and methods that involve all possible factors and actors in the landscape management, including farmers, scientists, and policymakers. The current study provides narrative baseline data and information on PTEs contaminations in Usangu agro-ecosystem agricultural soils, particularly in rice and maize growing areas. The temporal assessment indicates that PTEs concentration in agricultural soils increases with time which later might seriously exceed the established maximum thresholds. Thus, to guarantee the environmental quality, safety, and sustainability, it is critical to establish monitoring and management programs to avoid further PTEs increases in agricultural soils and linked food chains.

#### **4.2.7. Surface water quality and P concentrations in paddy farming areas to establish eutrophication risks**

##### **(i) Water pH**

The water pH is an indicator of the acidity or alkalinity of water samples but is seldom a problem by itself (Ali *et al.*, 2016). Generally, the acceptable pH range for irrigation water is 6.5 to 8.4, while pH values outside this range usually are associated with nutrient imbalance or may contain ions at toxic levels (FAO, 1985). Most natural waters have a pH of 5 to 8.4. High pH values above 8.5 are often associated with high carbonate ( $\text{CO}_3^{2-}$ ) and bicarbonate ( $\text{HCO}_3^-$ ) concentrations. The determined water pH trend in Usangu agro-ecosystem were in range of 4.8 to 7.9 (Table 50). Where water samples in intakes had higher pH values (5.3-7.2) closer to acceptable range (slightly acidic) while water samples collected in channels, fields, and drainages were acidic (low pH 4.9 to 7.9) (Fig. 24, Table 50 and 52). The comparison of water pH in different schemes in Usangu agro-ecosystem evidenced that some schemes had very low pH, such as Uturo and Kapunga, which might cause restrictions to plant growth and aquatic ecosystem but also may affect water quality and make water resources unfit for agricultural and domestic uses. In addition, Kapunga and Mubuyuni irrigation schemes were observed to have very variable pH (Fig. 24, Table 51) indicating deterioration of water quality. Generally, some of the determined water pH values were below minimum acceptable limit (6.5), suggesting management actions are required to return pH to normal range (6.5 to 8.4). This is possible through seasonal monitoring and identification of causative agents for reduced pH and inclusion of basic cations, organic manure, and the minimization of soil erosion, but also drainages from farming areas and urban areas which are enriched with protons ( $\text{H}^+$ ) might also be a contributor to increased water pH change in the agro-ecosystem; thus management strategies have to be in place like the use of field buffer or riparian buffer to control movement and filter water from fields before entering rivers and other water resource reservoirs.

##### **(ii) Electrical conductivity (EC)**

The EC determines the capacity of water to conduct electric current by various available ions i.e.,  $\text{Cl}^-$ ,  $\text{Na}^+$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^{2-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{Ca}^{2+}$ , and  $\text{Mg}^{2+}$  (Marchese *et al.*, 2008; Visconti & Paz, 2013). Furthermore, EC estimates total dissolved salts and salinity in irrigation water; thus, low EC indicates low dissolved salts concentration and *vice versa*. Generally, irrigation water with  $\text{EC} < 3000 \mu\text{S}/\text{cm}$  is free from salinity and better for crop production (FAO, 1985).

Plants take up water through osmoregulation; thus, elevated levels of salt concentration restrict or inhibit the ability of plants to take up water and nutrients (Ali *et al.*, 2016; Elisa *et al.*, 2021; Kihwele *et al.*, 2018). The EC of studied water samples from Usangu agro-ecosystem (UA) were observed to range from 30 to 2130  $\mu\text{S}/\text{cm}$  with a mean value of 202  $\mu\text{S}/\text{cm}$  (Table 50). Therefore, based on the determined EC, irrigation water in UA classified to have low salinity risks and less water use restrictions. The EC values among different sampling points (i.e., intakes, channels, fields, and drainages) showed that water in drainages and paddy fields had higher EC than intakes and channels (Table 52), indicating that anthropogenic farming activities are responsible for increased salt concentration in water resources. The EC spatial distribution in Usangu irrigation schemes found that schemes such as Kapunga, Ilaji, Ihahi, Igalako, and Mahongole had higher EC of more than 208  $\mu\text{S}/\text{cm}$  (Table 51). Therefore, irrigation water in the UA has lower salinity risk and can be used as a source of irrigation water without serious restrictions (FAO, 1985).

### (iii) Carbonates ( $\text{CO}_3^{2-}$ ) and bicarbonate ( $\text{HCO}_3^-$ )

Carbonates and bicarbonate ( $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$ ) in irrigation water are important as it has a close association with  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . Both  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  react with  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$  in water and soil to form  $\text{CaCO}_3$  or  $\text{MgCO}_3$ , respectively (Fipps, 2003; Guo *et al.*, 2021; Marchese *et al.*, 2008; van der Lee *et al.*, 2021). The precipitation of either calcium or magnesium from water as carbonate salts increases the relative proportion of sodium, thus increasing the sodium hazard rating (Ali *et al.*, 2016; FAO, 1985). The acceptable range of  $\text{HCO}_3^-$  content in irrigation water is 91.5 to 519 mg/L. Where excessive bicarbonate in irrigation water is toxic to roots and reduces shoot growth, reduces P uptake, and other micronutrients availability. Where  $\text{HCO}_3^- > 519$  mg/L can severely affect irrigation equipment and crops.

The concentration of  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  in studied water samples from UA were 42.7 to 189.1 mg/L for  $\text{HCO}_3^-$  and 1.10 to 48.4 mg/L for  $\text{CO}_3^{2-}$  (Table 50). It was found that the determined  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  values were within the acceptable range for irrigation water (91.5 to 519 mg/L). The determined values are expected to cause slight to moderate restrictions to crop growth (FAO, 1985; Suarez, 2011). Since the ( $\text{HCO}_3^-$ ) values are within acceptable range for irrigation water, the Usangu water resources can be considered suitable for irrigation purposes based on the current study (FAO, 1985). Concentration of  $\text{HCO}_3^-$  in collected water samples among different sampling points were in the order of; **drainages** (61.0 to 189.1 mg/L) >, **in fields** (58.0 to 183 mg/L), > **Channels** (100.7 to 149.5 mg/L), > **intakes** (42.7 to 119 mg/L),

and the same trend were observed for  $\text{CO}_3^{2-}$  (Table 50). In all locations, water samples from intakes were observed to have low  $\text{HCO}_3^-$  (42.7 to 119 mg/L) and  $\text{CO}_3^{2-}$  (1.10 to 24.2 mg/L) compared with other sampling points; this might be contributed by less disturbance at most water intakes in Usangu agro-ecosystem. But also higher  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  in subsequent water sampling points indicates that farming and other associated anthropogenic activities taking place in Usangu agro-ecosystem and nearby areas are responsible for increased carbonates concentration. The spatial  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  distribution among irrigation schemes were observed to vary markedly among schemes in Usangu agro-ecosystems, where Igalako, Ihahi, Ilaji, Kapunga, and Mahongole had higher values which were linked to intensified farming.

#### **(iv) The $\text{NH}_4\text{-N}$ , $\text{NO}_3\text{-N}$ , and total-N concentration**

Nitrogen (N) is essential for plant and animal growth, but N overabundance in irrigation water has detrimental health and ecological effects (Diatta *et al.*, 2020; Sangeetha & Ambujam, 2021; Schullehner *et al.*, 2017; WHO, 2016). Excess N can cause overstimulation of aquatic plants and algae growth, leading to lake and reservoir eutrophication, affecting fish, animal and plant diversity. If excessive quantities of N present or applied, the production of several commonly grown crops may be upset because of over-stimulation of growth, delayed maturity or poor quality. Thus, excess nitrate and nitrites in drinking and irrigation water are hazardous to human and aquatic life. The amount of allowable nitrate in drinking water is 50 mg/L, 0.01 mg/L for nitrite, and 0.5 mg/L for ammonium ions (Weissman *et al.*, 2020). The concentration of  $\text{NH}_4\text{-N}$  content in water samples from Usangu agro-ecosystem were observed to range from 8.6 to 70.0 mg/L;  $\text{NO}_3\text{-N}$  is 0.1 to 33.9 mg/L and Total N was 8.9 to 103.9 mg/L (Table 50). Some of these determined concentration values ( $\text{NH}_4\text{-N}$  and Total N) were more than those recommended for drinking and irrigation water (50 mg/L). Most crops are sensitive to excess nitrogen in irrigation water above 5 mg/L; however, most crops can tolerate N-concentration until 30 mg/L before leading to poor crop growth and reduced productivity. The study by Suarez (2011) reported that there was almost no fruiting in grapes irrigated with water with  $\text{N}>50$  mg/L in Libya. The maturity of fruit such as apricot, citrus, and avocado were observed to be delayed, and the fruit of poor quality were produced. Therefore, excessive N in irrigation water in any form is dangerous to crop productivity and environment.

The study found that concentration of  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and total-N in water samples varied with sampling points in paddy farming areas (Table 52). The determined concentration in different water sampling points were;  $\text{NH}_4\text{-N}$  in intakes (5.7 to 29.4 mg/L), channels (8.7 to 19.88 mg/L),

fields (11.2 to 35.8 mg/L) and drainages (9.5 to 70.3 mg/L). The same trend were observed for  $\text{NO}_3\text{-N}$  and Total-N (Table 52, Fig. 25). The study evidenced that N concentration in water samples increased once the water reached paddy growing areas or was higher in paddy growing areas than intakes, indicating that increased N in water was associated with agrochemicals and organic manure utilization and other anthropogenic practices happening within agro-ecosystems. In some sampling points  $\text{NO}_3\text{-N}$  and TN were lower in the drainages than in the fields are likely due to the denitrification process which reduced  $\text{NO}_3$  to gaseous end products ( $\text{N}_2\text{O}$  and  $\text{N}_2$ ) (Hu *et al.*, 2020, 2016, 2015). The higher N concentrations indicate signs of water eutrophication as they contain  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  enrichment which exceed 1 mg/L.

The spatial distribution of N in water samples in the study area was observed to vary from place to place (Table 51), where schemes located in highly intensified areas such as Kapunga, Mahongole, Igalako, and Mubuyuni recorded high  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and Total-N concentration in water samples (Table 51). This indicates that farming activities and other anthropogenic activities happening in Usangu agro-ecosystem might be responsible for increased  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and Total-N concentration and eutrophication phenomenon. Denitrification to remove  $\text{NO}_3\text{-N}$  from water supply before use may be the only other alternative but is not used because of the high cost of equipment and energy; since nitrogen is a valuable resource, it should be utilized if possible.

#### **(v) Total phosphate in water samples in Usangu agro-ecosystem**

Phosphorus (P) is essential for plant growth but has a severely detrimental effect when available in excess amount ( $\text{P}>0.1$  mg/L) in irrigation water, leading to eutrophication (Sánchez-Carrillo *et al.*, 2011), and increased excessive growth of phytoplankton, algae blooms, excess aquatic plant growth, and water quality degradation (Khan & Ansari, 2005; Sánchez-Carrillo *et al.*, 2011). Increased use of agrochemicals increases yield per unit area and is an important factor for increased P in water bodies (Gikuma-Njuru *et al.*, 2017b, 2017a; Moss, 2008). The concentration of P in static superficial water (ponds and lakes) and moving water (rivers and channels) in the natural ecosystem are usually low ( $\text{P}<0.01$  mg/L), this helps to keep the system stable (De Bolle, 2013; Fischer *et al.*, 2017; Hongthanat, 2010; Sato, 2003). The total P concentration determined in water samples from Usangu agro-ecosystem were in a range of 0.01 to 1.65 mg/L, where some sites had total P above 0.1 mg/L, a proposed limit for P concentration in freshwater reservoirs, thus posing a eutrophication threat in agro-ecosystem water resources. Determined total P were observed to vary among sampling points, where P in

water increased from intakes (0.01 to 0.04 mg/L), channels (0.01 to 0.13 mg/L), in fields (0.01 to 0.54 mg/L), to drainages (0.02 to 1.65 mg/L), indicating P enrichment in irrigation water from paddy fields (Fig. 26). This data confirms that P enrichment as the irrigation water passes through paddy system, evidencing agricultural activities being responsible for increased P concentration in water samples (Fig. 26). As well established that the concentration of P in stream waters in UA has been increasing since 1980s due to industrialization, urbanization, agricultural intensification, and rock phosphate mining activities in both East African agro-ecosystems (Sitoki *et al.*, 2010).

The spatial P distribution in irrigation water in Usangu agro-ecosystem was observed to vary among schemes where water samples from Ilaji, Igalako, Kapunga, and Chimala recorded high P concentrations (Table 51, Fig. 26). On the other hand, water samples from Ruaha and Uturo recorded very low P concentrations (<0.1 mg/L) in water samples (Fig. 26) due to less anthropogenic activities. Exceptionally, the concentration of total P in Ihanhi and Kapunga rice farm, the state own farm and highly intensified paddy farm were observed to be greater than 1.65 mg/L in some drainages, channels, and paddy fields indicating P enrichment from paddy farming areas. Thus, based on the determined P, water status in Ihahi and Kapunga farm had eutrophic (eutrophication) status. The results of this study are in line with results by Mshana (2015), who reported an appreciable amount of P in Lake Rukwa as influenced by agricultural intensification near the lake; the same scenario was observed in Lake Victoria by Gikuma-Njuru *et al.* (2017a) who reported 39.6 to 92 µg/L of P. A more interesting comparison of previous data indicates that the concentration of P in water reservoirs in Usangu basin increases over time as a result of anthropogenic farming activities and urbanization. Despite the importance of this information in water quality management, this information is currently limited in most Tanzania agro-ecosystem, more research studies are needed to further monitor P levels in water in streams and ponds in farming areas to develop detailed management strategies to ensure safe and sustainable water use in agro-ecosystems.

#### **(vi) Calcium, magnesium and trace metal concentration (Cu, Zn, Fe)**

Trace metals (TMs) such as Co, Mn, Fe, Zn, Cu, and Se are plant micronutrients at low concentrations required for plant growth; however, in high concentrations have potential toxicity effects on soil invertebrates, plants, and animals (Qin *et al.*, 2021; Renu *et al.*, 2021). The increased use of agrochemicals to increase land productivity, industrialization, and urbanization near farming areas can potentially increase TMs accumulation in paddy wetland

soils and water as these elements are impurities in most pesticides, herbicides, and inorganic fertilizers commonly used. The increased TMs in agricultural soils and water can increase TMs in crop grains, thus leading to environmental and health risks to animals and humans (Lü *et al.*, 2021; Paithankar *et al.*, 2021; Zhou *et al.*, 2021). Thus, TMs assessment in water in Usangu agro-ecosystem was important for agro-ecosystem quality assessment and management due to the current increasing agriculture intensification in the area involving increased use of herbicides, fertilizer, pesticides, and surface runoffs from urbanized areas for irrigation. The discussion of TMs assessed were as follows:

**Iron, magnesium, and calcium:** The concentration of Fe, Mg, and Ca in collected water samples in Usangu basin were: Fe (2.44 to 105 mg/L), Mg (38.55 to 227 mg/L), and Ca (3.86 to 22.7 mg/L) (Table 50). The assessment of these elements in different water sampling points in the agro-ecosystem observed significant variation such as; Fe in Intakes (3.41 to 9.76 mg/L), Channel (3.90 to 3.98 mg/L), Field (3.41 to 105.4 mg/L), and Drainages (2.93 to 86.3 mg/L); Mg intake (60.24 to 135 mg/L), Channel (38.55 to 62.7 mg/L), Field (67.47 to 227 mg/L), and Drainages (81.93 to 125 mg/L); Ca intakes (6.27 to 135 mg/L), Channel (3.86 to 6.27 mg/L), Field (6.75 to 22.7 mg/L), and Drainages (81.19 to 125.3 mg/L) (Table 52). Despite the fact that Fe is involved in plant biochemical reactions such as photosynthesis, it is important for crop growth. However, extreme concentrations (>5 mg/L) can limit the availability of other elements such as P and Mo through soil acidification, fixation, and sorption reactions, as well as have toxicity effect on plants (Amuri *et al.*, 2012; Karlsson & Messing, 1980; Mhoro & Anthony, 2015; Ndakidemi & Semoka, 2006).

The spatial distribution of Fe, Ca, and Mg in water from different irrigation schemes showed significant variation, where schemes such as Mahongole, Ihahi, Igalako, Chimala, and Ilaji had higher Fe (8.17 to 105 mg/L), Ca (10.42 to 17.5 mg/L), and Mg (104 to 202 mg/L) (Table 50). A ratio of Ca/Mg of less than 1 in irrigation water has been known to reduce the productivity of crops such as barley, paddy, maize, and sugarbeets; the same scenario was observed in water from Usangu agro-ecosystem where the ratio of Ca/Mg were 0.1 (less than 1) and reverse (Mg/Ca) ratio were above 10 indicating Mg were more in irrigation water, which can be associated with negative impacts on crop productivity, due to limitation in uptake and translocation of Ca from soil-water to above-ground parts of the growing crops. The high Mg concentration in irrigation water can be associated with reduced crop productivity in agro-

ecosystems because magnesium-induce calcium deficiency (FAO, 2021). Therefore, the Usangu agro-ecosystem water quality potentially limits crop nutrition and therefore yield.

The determined Fe in studied water samples from UA were above 5 mg/L, a maximum acceptable threshold for Fe in irrigation water (Table 51), especially in water samples collected from fields and drainages except for Uturo, Ruaha, and Ilaji which had Fe concentration within acceptable limit of 5 mg/L (FAO, 1985, 2021; Horneck *et al.*, 1999). The study generally found that concentrations of Fe, Ca, and Mg in Usangu agro-ecosystem water samples were above the concentration ranges of natural water, indicating degradation in water qualities which might be a result of agricultural activities and other associated activities in the basin.

**Copper and zinc** concentrations in the study area were observed to vary across irrigation schemes and sampling points. The Cu and Zn concentration in water samples studied was in the range of 0.35 to 1.23 mg/L for Zn and 0.12 to 0.31 mg/L for Cu. The observed values in all schemes were above the acceptable limit of 0.2 mg/L of Cu in irrigation water; this might be influenced by the use of Cu-based agro-chemicals commonly used in paddy farming and horticultural crop production in the area (Kihwele *et al.*, 2018; Machibya & Mdemu, 2005; Mongi *et al.*, 2020). However, some plants are reported to tolerate Cu concentration in irrigation water up to a concentration of 1 mg/L (FAO, 1985, 2021). The Zn and Cu spatial distribution in water were significantly different ( $P<0.05$ ) among schemes and sampling points, where all schemes had Cu concentrations ranging from 0.12 to 0.31 mg/L. Irrigation schemes such as Kapunga, Mahongole, Ruaha, Uturo, and Chimala were observed to have higher Cu concentrations (Table 51). The observed values in all schemes were above 0.2 mg/L, the acceptable limit of Cu in irrigation water. The concentration of Cu in different sampling points were significantly different where their values were: intakes (0.25 to 0.29 mg/L), channel (0.19 to 0.30 mg/L), paddy fields (0.12 to 0.31 mg/L), and drainages (0.19 to 0.31 mg/L). The observed Cu concentrations were higher in water samples from fields and drainages exceeding the limit; thus potentially leading to adverse environmental impacts such as plant toxicity. The observed Cu concentrations were higher in water samples from fields and drainages; however, some intakes also had appreciable levels of Cu, which might be influenced by Cu-contaminated runoff, wearing from brake linings, vehicular emissions from nearby highways and residential areas as supported by Malunguja *et al.* (2022).

The spatial distribution of Zn was different across the water types. All schemes had Zn concentration in the range of 0.61 to 0.82 mg/L, where Mahongole, Igalako, Ruaha, and Ihahi

had higher values (Table 50 and 51). All samples had Zn concentration below 2.0 mg/L, the acceptable threshold of Zn in irrigation water. However, Zn concentration in studied water samples was within the acceptable threshold (2.0 mg/L); Zn concentration in various sampling points ranged from 0.35 to 1.23 mg/L, where channels, fields, and drainages had higher Zn concentrations than intakes (Table 52). This indicates that concentration of Zn in water from Usangu agro-ecosystem might be influenced by anthropogenic activities conducted in the area; however, their values are still within acceptable limits of Zn in irrigation water. Generally, the data presented here clearly show the need for farmers and regulatory authorities to take all necessary initiatives to monitor and maintain irrigation water quality in paddy wetlands for optimum crop productivity and improving the quality of drainage water re-entering the catchment downstream of the paddy systems in Usangu agro-ecosystem.

#### **4.2.8. Potential accumulation of PTEs from soils to plant tissues (bioconcentration) in Usangu agro-ecosystem**

The build-up of PTEs in agricultural soils may accelerate uptake by plants to different plant parts but also can be transported to far distances through food products such as grains, straws, and fodders, which could potentially affect food quality and safety. Here status and bioaccumulation of PTEs from soils to plant parts (roots, stem, and grains) in Usangu agro-ecosystem were characterized. The paddy rice plant samples were used as a dominant crop in Usangu agro-ecosystem. To achieve this, 68 soil and 42 rice plant samples from six irrigation schemes were analyzed for Cd, Cr, Cu, Pb, Zn, Ni and Fe to estimate accumulation, distribution, translocation, and bioconcentration.

##### **(i) The distribution of total PTEs concentration in agricultural soils**

The determined PTEs concentrations in soil samples collected from where paddy rice plant samples were collected from different irrigation schemes was significantly different ( $P < 0.05$ ). Where the mean values of total PTEs in agricultural soils (mg/kg) were Cr (15.39), Co (2.92), Fe (7371.18), Zn (18.25), Cd (0.02), Cu (3.34), Ni (4.11), and Pb (5.66) (Table 51). Among the studied PTEs, Fe and Co concentrations were found to be above Tanzania's permissible limits in soils and natural habitats (URT, 2007), where 99.48% among 68 studied soils had Fe concentrations above-established limit. This indicates that the system is enriched with PTEs, which might affect environmental quality and food safety. The comparison of PTEs concentrations in agricultural soils in the Usangu basin and other parts of Mbeya and Njombe

districts determined in 1999 by FBD (2007) and Fox (2004), it was found that PTEs concentration in agricultural soils in UA increases with time. The increasing PTEs in agricultural soils in Usangu might be associated with increasing anthropogenic activities in the area and nearby areas, which later determines the PTEs accumulation and distribution. The concentration of PTEs determined was observed to be at a level to be sufficient to trigger injurious effects on soil invertebrates, animals, and humans.

The PTEs spatial distribution among irrigation schemes in Usangu basin were found to be significantly different ( $P < 0.001$ ). The trends observed that irrigation schemes locations had an influence on the concentration of PTEs in agricultural soils, where lowland schemes were observed to have high PTEs concentration ( $P < 0.001$ ) such as Cr, Pb, Co, Fe, Ni, and Cu than their counterparts (Table 53). This could be potentially influenced by downstream runoffs from highland areas and agricultural intensification (Ngailo *et al.*, 2016). Highly commercialized and intensified schemes such as Kapunga, Mabadaga, and Mubuyuni (Table 53) had higher PTEs concentration, which might be exacerbated by increasing application of agrochemicals which has been reported to be associated with PTEs impurities, vehicular emission from machines and vehicles working in farming and nearby areas could be another reason for increased PTEs in soils (Wang *et al.*, 2008). Furthermore, farming areas or irrigation schemes that were closer or located closer to residential areas such as Igalako, Mabadaga, and Mahongole were observed to have significantly higher Zn and Cd concentrations; this can be due to runoffs, effluents, and emissions from urban areas and domestic wastes (Shemdoe, 2010). Conclusively, it was found that concentration of all studied PTEs in all irrigation schemes where paddy rice plant samples were collected were within acceptable limits except for Fe and Co.

## **(ii) The PTEs accumulation in plant samples**

To estimate the risk of PTEs that can accumulate in the food chain leading to health risks to animals, soil invertebrates, and humans characterized by estimating the PTEs in whole plant samples and in separate plant parts (grains, straws, and roots) (Table 54 and 55) (Srivastava *et al.*, 2017). The total PTEs concentration (in mg/kg) determined in whole plant samples were in a range of “Cu (5.2 to 33.6), Zn (57.0 to 120.9), Fe (963.5 to 27919.0), Mn (613.2 to 2281.0), Cd (4.3 to 17.5), Pb (0.01 to 28.3), Cr (12.9 to 57.4) and Ni (9.7 to 103.3) (Table 54). The determined PTEs concentration was higher than those obtained in soil samples (Table 34), indicating the accumulation of PTEs from soils to plant tissues. The PTEs concentration in

plant samples among irrigation schemes was observed to vary significantly between schemes ( $P < 0.001$ ), where schemes such as Igalako, Mubuyuni, Ihahi, and Mahongole had a higher Pb, Cu, Fe, Zn, and Ni concentration. In addition, Kapunga and Uturo had higher Fe, Mn, Cd, Cr, and Ni concentrations in plant samples (Table 55). The overall trend for PTEs distribution in plant samples across irrigation schemes was observed to be significantly different where high values of most PTEs were observed in Mubuyuni, Mahongole, Ihahi, and Igalako (Table 54 and 55), the same trend as PTEs observed in agricultural soils (Table 34). Based on the “Food and Agriculture (FAO) and World Health Organization (WHO) of the United Nations maximum tolerable limits of PTEs in a food product (in mg/kg) such as Fe 425, Cu 2, Zn 60, Cd 0.5, Pb 2 and Mn 100” (Choi, 2011; Koleleni & Mbike, 2018), the total PTEs concentration determined in plant samples for Cd, Mn, Fe, Cu, Pb, and Zn were above the WHO permissible limits, that means the determined PTEs could cause health risk to animal and human using that plant products or fodders (Koleleni & Mbike, 2018; Simon *et al.*, 2016). However, the concentration of PTEs in paddy rice grains the common edible portion of paddy rice were within the acceptable WHO limits. Generally, Cu and Zn have known to have the most serious physiological and cellular damage in paddy plants. Increased Cu and Zn concentrations in soil and plant parts may cause cellular damage and nitro-oxidative stress, causing the function of reactive oxygen and nitrogen species metabolic enzymes to be disrupted and protein output to be reduced owing to proteolysis. The high availability of PTEs in plant samples poses an environmental and ecological danger, as higher PTEs uptake by soil invertebrates, animals, and humans via contaminated food chains and surface water has been linked to negative consequences (Ordóñez *et al.*, 2003). The general trend for PTEs distribution in plant samples among irrigation schemes studied was significantly different, with high values of most PTEs observed in Ihahi, Mubuyuni, Igalako, and Mahongole (Table 53 and 54), as well as the same PTEs trend observed in agricultural soils, indicating the influence of PTEs in agricultural soils on PTEs levels in plant tissues in the area” (Mng’ong’o *et al.*, 2021a).

### **(iii) The PTEs distribution in paddy rice plant parts**

The consumption of high levels of PTEs in edible food crops or fodders has been linked to a risk to human and animal health. As a result, determining the soil-to-food-crop relationship in terms of PTEs buildup is necessary (Malidareh *et al.*, 2014). The accumulation of PTEs in soil and plant parts can have a far wider impact beyond contamination areas via food and fodders. Contaminated grain, for example, can be transferred to markets in nearby cities and

neighbouring nations, posing health risks to humans once consumed. Estimating total PTEs from edible and non-edible plant components may be less informative. Hence determination of PTEs in grains, straws, and roots separately is recommended and was conducted in this study. In this study, the PTEs were divided into three principal plant sections: roots, straws, and grains. Whereas roots indicate PTEs concentrations that can be found for soil decomposers, straws reflect PTEs concentrations that can be found in animal fodders. The PTEs determined in grains are available for human and animal ingestion through rice grain eating. The PTEs concentrations varied significantly ( $P < 0.01$ ) among plant sections. The PTEs concentrations varied widely among plant parts, however, straws and roots consistently had greater PTEs contents than grains in all irrigation schemes (Table 55, Fig. 29). Animals feeding on rice straws after harvesting are at risk due to the high concentration of PTEs in the straws determined. But also, when crop leftovers are integrated into agricultural soils, PTEs are returned to the soil, increasing the threat of PTEs to soil microorganisms and invertebrates. The distribution of PTEs in various plant parts was found to be significantly varied ( $P < 0.05$ ). Generally, PTEs levels were found to be greater in straws and roots than grains. The concentration (in mg/kg) of some PTEs in plant parts were; **Zn** in roots (29.3 to 68.2), straws (23.1 to 49.3), and grains (14.7 to 34.5); **Pb** in roots (ND to 9.47 mg/kg), straws (ND to 9.42 mg/kg) and grains (ND to 9.42 mg/kg); **Cu** in roots (4.54 to 22.08), straws (1.8 to 6.9), and grains (ND to 6.3); and **Cd** in roots (1.7 to 3.7), straws (1.7 to 8.9) and grains (1.4 to 2.2).

Plant samples from Ihahi, Mubuyuni, and Uturo had Pb concentrations below detection limits in all plant parts (Table 53), followed by Kapunga irrigation schemes, which had very low Pb concentrations in all plant parts such as roots (0.271 mg/kg), straws (0.274 mg/kg), and grains (0.270 mg/kg) (Table 55). In Mahongole and Igalako, on the other hand, greater Pb concentrations in plant parts were found, ranging from 9.41 to 9.46 mg/kg for Mahongole and 6.7 to 6.84 mg/kg for Igalako. The Ni, Cr, Fe, and Mn concentrations in roots and straws followed the same trend as Cd, Cu, Pb, and Zn, with higher PTEs concentrations in roots and straws than in grains (Table 55). The high PTEs concentration in plant roots than in other plant parts shows that the translocation of studied PTEs was low or limited to roots and straws.

The concentration of PTEs in rice grains, the edible part of the paddy rice, was lower than in other plant parts. The concentration of PTEs in rice grains were observed to be within acceptable WHO/FAO maximum tolerable limits (Table 12). The PTEs concentrations in paddy rice studied samples were in the order of decreasing as  $Fe > Mn > Cd > Cu > Zn > Ni > Cr$

> Pb. The fodders may be associated with health risks because the levels of some PTEs exceeded the permissible limits, the same scenario observed by Duan *et al.* (2021) and Araujo *et al.* (2022) in maize plant tissues in Southwest China and protected areas of Santa Cruz Brazil. These PTEs in different paddy rice plants parts were in the order of decreasing as roots > straws > grains (mg/kg), showing that less PTEs accumulated in grains than in other parts; thus, less health risks were associated with rice grains. This demands concern, particularly in the case of Pb and Cd, which are highly toxic and of no known biological use. Therefore, monitoring and management of PTEs levels in agricultural soils are important because the production of food and fodder crops in PTEs contaminated fields pose health risks due to its accumulation in plant tissues.

#### **(iv) The translocation and bioconcentration factors of PTEs in plant samples**

As there is a clear relationship that elevated levels of PTEs in farming areas may fast-track the uptake of PTEs in plant systems and grains (Liu *et al.*, 2015; Miras *et al.*, 2011; Zhou *et al.*, 2014). The elevated PTEs in soils increase its levels in plant parts such as roots, grains, and straws, leading to health risks (Simon *et al.*, 2016). The bioconcentration factor (BCF) explains the transfer and bioavailability of PTEs from soil to plants or plant edible parts (Lugwisha, 2016). Where the BCF of above 1 indicates a higher uptake of PTEs in crop/plant than in soil, while BCF of less than 1 indicates more PTEs concentration in soil than those taken up by plants (Lugwisha, 2016). In this study, the BCF in paddy rice plant samples from UA determined observed to be significantly different ( $P < 0.05$ ) among schemes (Table 56). The BCF for studied PTEs were as follows; Cr (0.7 to 2.7), Fe (0.9 to 7.8), Zn (4.3 to 6.9), Cd (177.3 to 863.3), Mn (3.3 to 8.4), Cu (3.1 to 15.6), Ni (2.0 to 11.6), and Pb (0.0 to 3.7). Where Cd, Zn, Mn, and Cu were observed to be favoured in accumulating in plant parts than other elements, as their BCF were above 1 for all schemes.

The BCF values determined among schemes observed that all schemes (100%) had BCF above 1 for “Zn, Ni, Mn, Cd, and Cu, indicating that the concentration of named PTEs was higher in plant samples than that determined in the soil. This indicates plants had higher PTEs uptake, which can contaminate grain and fodders, leading to health risks to humans and animals. The study showed that all schemes had low BCF for Cr, Fe, Zn, and Pb, which indicates that less PTEs were in plant samples tissues compared with PTEs in soils. Outstandingly, the study found that Igalako and Mahongole schemes had BCF above 1 for Pb, and only 33.3% of the studied samples had BCF above 1 for Pb (Table 56). Furthermore, it was observed that high

BCF values for Cd (177.3 to 863.3) were across all irrigation schemes (Table 56). This indicates that maybe paddy rice plants had a high affinity to Cd, and low Cd observed in soils that might be affected by management practices. Higher BCF ( $>1$ ) for some PTEs in some schemes point out that there is a risk of accumulation of PTEs in the food chain leading to health risks to humans and animals. This study is in line with the study by Lugwisha (2016) that determined BCF of Cd, Cu, Pb, and Zn in tomatoes, cauliflower, cabbage, and carrots in Morogoro region-Tanzania, where greater than 1 BCF values were obtained in some study sites, where such high BCF values suggested that studied leafy vegetables and tomatoes were associated with health risk to consumers” (Mng’ong’o *et al.*, 2021a).

The translocation factor (TF) describe the movement of PTEs from soils to roots (below-ground biomass) to straws and grains (above-ground biomass). Based on the TF, a large concentration of PTEs was observed to accumulate in the below-ground biomass (roots) than in the above-ground biomass (straws) (Table 56). This study found that TF values for studied PTEs were as follows: Cr (0.27 to 2.33), Fe (0.02 to 0.35), Zn (0.62 to 1.00), Cd (0.68 to 1.25), Cu (0.27 to 0.75), Ni (0.65 to 1.15), Pb (ND to 1.00), and Mn (0.53 to 1.40) (Table 54: ). It was observed that TF values for Cr, Zn, Cd, Ni, Pb, and Mn were above 1, i.e., 33.33, 33.33, 16.67, 50.00, 33.33, and 50.00%, respectively (Table 56) of the studied samples had TF above 1 for Cr, Zn, Cd, Ni, Pb, and Mn. This indicates that the translocation of PTEs was higher to shoots or straws than roots which shows more transportation of PTEs from roots to straws (Table 56). It was observed that Mubuyuni and Ihahi irrigation schemes had higher TF values for most of the PTEs studied. On the other hand, the TF values for Fe and Cu were observed to be below 1 ( $TF < 1$ ) in all studied schemes indicating that the concentration of Fe and Cu was higher in roots than in straws in all studied plant samples in all irrigation schemes (Table 56, Fig. 31). The general trend for PTEs translocation factor based on this study it was found that TF values for most elements studied were below 1 in more than 75% of the studied schemes indicating that there was less translocation of PTEs from roots to straws or in other words more PTEs were found to be accumulated in below-ground biomass (roots) than above-ground biomass (straws and grains). Based on the determined TF for PTEs studied, it is clear that in paddy farming areas of Usangu agro-ecosystem, the risk of PTEs is less in edible plant parts compared to below-ground biomass, however, the paddy rice straws might be associated with health risk compared to grains.

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

#### 5.1. Conclusion

The assessed scope and parameters in this study provide information on (i) soil quality and invertebrate (earthworm) biodiversity as impacted by current land use, (ii) soil nutrient dynamics and availability as measure of land productivity and sustainability, (iii) PTEs accumulation and pollution risks to soil inhabitants, plants and animals, and (iv) water quality of surface freshwater resource in the landscape. Furthermore, this thesis highlighted the importance of accounting for PSC, PSD, P sorption and desorption for sustainable P management and environmental quality in farming areas, an important aspect that is often overlooked, especially in most land productivity and sustainability studies in most tropical soils. Thus, this final chapter synthesizes and provide major findings of study and its implications for agro-ecosystem productivity, environmental quality management and sustainability. The chapter concludes by suggesting to scientific community, policymakers, and farmers the monitoring, management options and conservation plans for this agro-ecosystem but also provide future research directions to be conducted in the area.

##### 5.1.1. The current soil fertility and sustainability in Usangu agro-ecosystem

The current soil fertility status in Usangu agro-ecosystem as assessed provides baseline data needed for monitoring and management to safeguard sustainable land production. Based on the studied soil fertility parameters indicates that overall soil pH ranged 6.4 to 7.6, where 10% of studied soils had pH less than 6.5, which can limit plant nutrient availability due to fixations and toxicity effects, thus, affecting crop yield. Most of studied soils had level of P, N, K, Ca, Mg, and some micronutrients like Zn at deficient amount. Thus, to achieve higher yield, addition of manure, synthetic fertilizer and other materials which are rich in plant nutrients is important to replenish plant nutrients so that to ensure increased capacity of the soil to support plant growth and higher productivity. Generally, farming areas observed to be more deprived of plant available nutrients than conserved areas, which are usually associated with less plant residues replenishment. The intensity of farming activity also take vital role in nutrient uptake and fertility status. In this study, it was found that P, N, and other plant nutrients concentration in paddy farming areas was most badly affected despite of receiving more N and P-fertilizer which likely to be due to higher nutrient loss as result of flooding irrigation practices in use in

the area. To ensure future land productivity and sustainability of UA, mineral nutrient decline have to be addressed in areas found to have deficiencies. Where to achieve this agenda farmer-based soil fertility management studies are needed which must involve integrative techniques.

### **5.1.2. Soil PSC and PSD indicator as an estimate for P fixation and loss**

Based on the estimated PSC (5.62 to 34.85 mmol/kg) Usangu agro-ecosystem agricultural soils classified to have low to high P sorption capacity status safeguarding high P holding capacity for plant uptake. But some soils were found to have very low PSC which likely to increase the risk of nutrient losses from agricultural fields to the environment. But also UA agricultural soils observed to have unsaturated P status ( $PSD < 24\%$ ), therefore there is lower risk of P loss from agricultural fields to other ecosystem. However, few soils and location in UA were observed to have PSD greater than 15% which with increasing fertilizer uses trend are likely to increase the P loss from agricultural fields to water bodies and reduced agricultural productivity. For that reason, fast and preventive arrangements for sustainable P management has to be in place to ensure land productivity, environmental safety, and sustainability.

### **5.1.3. PTEs accumulation and pollution risks in soils and plants in UA**

The accumulation of PTEs in agricultural soils and plants determined among land use and irrigation schemes observed to be variable and most of them were within Tanzania maximum permissible limits (MAL) indicating that their concentrations is not high enough to cause serious toxicity effect to soil inhabitants, plants and animals in the area. However, concentration of some PTEs such As, Se, Co, Fe, and Mo concentrations exceeded MAL for PTEs in agricultural soils, thus they may compromise soil quality and affect the productivity of agro-ecosystem due to limitation of plant nutrient availability and toxicological effects to plants and soil microbes. But also farming areas and conserved areas near residential areas and highways were observed to have higher PTEs which associated with urban effluents and emissions as the addition source of PTEs in agricultural soils. Generally, based on the contamination hierarchy established, farming areas observed to be more prone to PTEs contamination and pollution risks than conserved areas in the landscape. Thus, important and intentional management options which increase productivity in farming areas while ensuring environmental quality and sustainability need to be introduced and implemented in UA. The accumulation of PTEs in plant materials were it was found that the ratio PTEs in plants and soil samples (bioconcentration (BCF)) was greater than 1 for some sites indicating higher PTEs

uptakes by plants which could potentially lead to possible health risks to soil invertebrates, animals, and humans. The PTEs accumulation in plant samples were observed to follow the same trend as those determined in agricultural soils indicating that elevated levels of PTEs in agricultural soils are likely to increase PTEs in plant tissues. The PTEs concentration in different plant parts such as roots, straws, and grains from paddy rice plant samples were observed to be higher in non-edible parts (such as roots and straws) compared with grains. The high PTEs concentration in paddy rice straws presents risks to animals that usually graze on rice straws in these areas after paddy rice harvesting, which can transfer the accumulated PTEs to human through meat and milk. Despite the fact that currently Usangu agro-ecosystem has a minimally polluted status, essential management strategies to avoid further PTEs accumulation in soil, water, and plants tissues have to be in place as the situation might worsen in the near future due to increasing urbanization, agro-mechanization, and intensification currently happening in UA.

#### **5.1.4. Surface water quality and eutrophication in Usangu agro-ecosystem**

The current water quality in paddy farming areas in Usangu agro-ecosystem observed to be in deteriorating status. Where the determined water pH (4.8 to 7.9) were mostly outside the acceptable pH range (6.5 to 8.4) for irrigation water, thus being associated with nutrient imbalance but also may contain ions at toxic levels. It was observed the water pH were observed to deviate from acceptable range as water move across paddy fields from intakes to drainages indicating they have been altered by anthropogenic activities from farming areas. The studied water samples had electric conductivity within acceptable range (2130  $\mu\text{S}/\text{cm}$ ) for irrigation water indicating that they were free from salinity risks, but their values observed to increase from intake to drainages. Water samples from Usangu were observed to have higher plant nutrients (N and P) and trace metals (Fe, Zn, Pb, Cd, Cu and Cr) which observed to increase in water samples from intake to drainages indicating they are likely to be originating from paddy fields. Some of the determined values were observed to be above acceptable limits for plant nutrients and PTEs in irrigation water indicating that currently there is water quality degradation in UA. The nutrient loss from paddy fields to water bodies through drainages are likely to affect the land productivity in the respective areas but also likely to affect aquatic ecosystem in a particular area and those connected to UA.

## **5.2. Recommendations**

Based on the data generated in the current study and their interpretation about soil fertility and phosphate status, sorption (PSC) and saturation (PSD); water eutrophications; PTEs accumulation, distribution and pollution indexes in Usangu agro-ecosystem, the number of the recommendations have been drawn which will initiate the process and practices which will improve the current status towards improved land productivity, environmental quality and sustainability of UA and other agro-ecosystem with similar characteristics in Tanzania. The recommendation ranges from practices of good agronomic practices, policy reviews and development of de novo adsorbent for P and PTEs capturing in water draining from agricultural fields, which will allow recycling of useful nutrients like P and prevent the transport of PTEs from agricultural fields to water reservoirs. The recommendation has been divided into three main groups where (a) recommendation to the scientific community on what to be done based on generated information through further research, (b) recommendation to policymakers on what to be reviewed and incorporated into existing policy to ensure land productivity, environmental quality, and sustainability of agro-ecosystem for the benefit of current and future generations, and (c) recommendations to farmers on what can be adopted to improve the current situation by using available resources, this is based on literature and evidence that the proposed practices or advice have been found to be practical and useful in other parts of the world with similar conditions as UA. All recommendation tries to highlight how further studies and practical implementations can help to improve land productivity, environmental quality and sustainability of Usangu agro-ecosystem and they are not intended to be exhaustive of all possible list.

### **5.2.1. Recommendation to the scientific community**

The recommendation to the scientific community on what can possibly be conducted to improve the current status of Usangu agro-ecosystem to ensure increased land productivity, environmental quality, and agro-ecosystem sustainability are highlighted as follows:

#### **(i) Review of current existing fertilizer recommendations**

The current existing fertilizer recommendation which is used by farmers as a guideline for soil fertility management in UA, to determine which and what amount of fertilizer should be used to ensure better land productivity need to be revised since are old and out of date since they are more than 30 years old but does not take into account PSC, PSD and nutrient bioavailability.

**(ii) Development and use of slow-releasing fertilizer in areas with high hydrological connectivity**

Currently, in Usangu agro-ecosystem and other agro-ecosystem in Tanzania, the same fertilizer types are used in the upland and lowland areas; the commercially available inorganic fertilizers are fast releasing fertilizer which is prepared to suit the upland farming areas with limited moisture content. Once these fast releasing fertilizers used in lowland areas with high hydrological connection and high moisture content, such as paddy farming areas, 60 to 70% is lost from agricultural fields to water bodies through runoffs, drainages or through leaching. Therefore, development and use of slow-releasing fertilizer mainly for P, which is a scarce and non-renewable resource, specifically in areas with higher hydrological connectivity like paddy farming areas will ensure slow and efficient plant nutrients (i.e., P) utilization.

**(iii) Development of adsorbent based on Al and Fe rich materials for P adsorption from water drainages from agricultural fields**

From the current study, it was found that water drainages from agricultural fields had a higher P concentration ( $>1.65$  mg/L) than in natural water. This shows that there is a high P loss from agricultural fields which ends up in water reservoirs. Thus, to protect water reservoirs from excessive P and ensure P recycling, this study recommends the development of a de novo P adsorbent based on Al and Fe rich materials (which have been observed to have a high affinity to P ions), which can be utilized to capture P from drainages from paddy fields. This will enable recycling of the P, which could have been lost to water bodies to cause eutrophication. The captured P can be used back in paddy fields, thus reducing the production cost and ensuring phosphate sustainability.

**(iv) Development of legacy P solubilizer**

This study found that agricultural soils in Usangu agro-ecosystem have higher total P, but less than 30% of it is bioavailable for plant uptakes. This shows that soil accumulates P from different sources such as added organic and inorganic fertilizer and complexes it to a form that is not easily soluble or available for plant and soil microbial uptake. This scenario reduces P fertilizer returns to farmers and increases amount of P available in the soil as legacy P, but it is unavailable for plant and soil microbial uptake. Thus, it is possible to develop a bio-based reactant (soil microbes), which will help to dissolve the legacy P and making it available for plant uptake.

#### **(v) Development of PTEs crop excluder**

The current study found the potential signs of PTEs accumulation in agricultural soils and water in UA, areas contaminated by PTEs limit the use, productivity and sustainability of agro-ecosystem. However, the availability of crops that can tolerantly grow in contaminated areas without accumulating PTEs in their plant tissues to toxic levels will be very useful due to the fact that arable land is decreasing and the only little available land should be utilized intensively. This study recommends that to ensure land productivity, environmental quality and sustainability of UA to develop PTEs crop excluder, either through biotechnology or conventional breeding programs. Crops that are capable of excluding PTEs from agricultural soils but absorb required plant nutrients will enable the production of safe food crops in contaminated areas or grow those crops using wastewater which is currently increasing while freshwater resources are decreasing due to drought and climate change.

#### **(vi) Development agrochemicals which are free from toxic metals**

Since fertilizer such as phosphatic fertilizer and other agrochemicals used in farming areas, Usangu inclusive have reported as being the greatest contributor of PTEs in agricultural soils, water, and plant tissues. It is necessary to develop or design fertilizer and other agrochemicals which have less levels of PTEs impurities through increased purifications process during production of particular agrochemicals. This can be achieved by finding and using different agrochemicals production options instead of relying on the use of natural materials like phosphate rocks in P-fertilizer production line. The alternative production option can be designed and explored to avoid the inclusion of elements that are not beneficial and detrimental to plants and microbes in soil and water.

#### **(vii) Introduction of riparian buffer zone**

In this study, it was found that areas that are closer to residential areas or which are in urbanized areas were found to be associated with certain PTEs than other areas which were far from residential or urbanized areas. But also, it was observed that drainages from agricultural fields had higher plant nutrients (N and P) and trace metals concentration. This indicates that the direct connectivity of farming areas to urban areas, rivers or water resources might affect environmental quality or sustainability of the agro-ecosystem. The introduction of a riparian buffer zone between farming areas and urban areas and between farming areas and rivers or water reservoirs is recommended. This will allow water to filter itself into the buffer where all

plants' nutrients and toxic elements will be left behind. Plants that are PTEs and plant nutrients accumulators should be planted in the buffer zone will further help to reduce the PTEs and plant nutrients concentration in draining water, thus reducing the risk of PTEs to agricultural soils and water reservoirs.

#### **(viii) Characterization of PTEs along the soil profile matrix and soil classification**

The current study characterized PTEs and plant nutrients on the top surface soils (0-30 cm), there is a need to characterize them along the soil profile to understand the vertical distribution of PTEs in agricultural soils but also to conduct soil classification in the area in detail because the availability of PTEs and plant nutrients are largely influenced by soil types and associated mineralogy of the area.

#### **5.2.2. Recommendation to policymakers**

In this study, it was found that some of the aspects which are required to improve the current status to increase land productivity, environmental quality, and sustainability of agro-ecosystem require policy review and imposition of by-laws by respective authorities. Therefore, this study recommends the following to be taken into consideration:

- (i) To initiate review and recommend fertilizer types used in paddy farming areas: Most paddy farming areas as Usangu agro-ecosystem have a high connection to hydrological networks. Thus, the use of highly soluble fertilizer in these agro-ecosystem reduces the fertilizer use efficiency as a large portion of added fertilizer is lost to the environment through leaching and surface runoffs. The commonly used inorganic fertilizer such as DAP, Urea, CAN, and TSP are highly soluble fertilizer and their use in paddy farming with flooding system of irrigation poses a high nutrient loss, environmental contamination, and environmental quality degradation. Therefore, the use of coated fertilizer (such as sulphur coated urea), a slow-releasing fertilizer in paddy farming areas will enable slow release of nutrients. This will ensure nutrient availability to plants, but less nutrients are lost to the environment, thus ensuring land productivity, environmental quality, and sustainability.
- (ii) To review agrochemicals which can be used in areas with high hydrological connections to avoid excess nutrient loss to water bodies. Some pesticides or agrochemicals are highly soluble in water, and some are highly poisonous; therefore,

following the increasing trend of agro-chemicals use in intensive farming will likely degrade water quality and connected ecosystem. Thus, it is important to review and select only authorized agrochemicals that have less residual effects on the environment without compromising land productivity and agro-ecosystem sustainability.

- (iii) To impose guideline for introduction of mandatory riparian buffer of at least 60 meters between agricultural fields and water reservoirs and between farms and residential areas. This will avoid leachates or surfaces runoffs from residential areas to agricultural land, but also drainages and surface runoffs from agricultural fields will be avoided to enter directly to water bodies. The riparian buffer could be planted with nutrient scavengers plants which will allow drainages that are free from toxic contaminants and excess plant nutrients.
- (iv) Review the irrigation system used in Usangu and provide guidelines to adopt techniques/system which uses less amount of water (sustainable system of rice intensification (SRI) or Kilimo Shadidi in swahili) and produce less contaminated drainages to down streams.
- (v) To reinforce the use of slow-releasing fertilizer in areas with high hydrological connections such as paddy farming areas in the low land areas.
- (vi) To introduce a large land use/cover area survey (LUCAS) to collect at least 3,000 soil samples in all major agro-ecosystem in Southern Highland Tanzania after every three years to analyze all land productivity and environmental quality parameters which will enable monitoring and management of agro-ecosystem sustainability.

### **5.2.3. Recommendation to farmers and other land users**

This includes the practices which have been observed to be potentially important to improve the current land productivity, environmental quality, and deterioration status. This includes practices that will ensure high land productivity for different crops produced in Usangu agro-ecosystem without compromising environmental quality and sustainability. The following are practices recommended to be adopted by farmers to improve the current status in Usangu agro-ecosystem:

(i) **Incorporation of organic manure in farming areas especially in paddy farming areas that rarely receive organic manure.**

The application of organic manure improves the soil chemistry such as soil pH, organic carbon, and cation exchange capacity of the soil but also increases microbial activity, which is very crucial in organic matter mineralization and plant nutrient recycling. But also, application of OM or manure which act as chelating agents that's bind Al and Fe, thus preventing formation of Al-and Fe-phosphates which tend reduce P availability, but upon mineralization organic manure release P and other nutrients.

(ii) **Split fertilization program**

This study found that most agricultural soils in Usangu agro-ecosystem have low nutrient (P) sorption capacity (PSC), high P saturation degree (PSD) and high rate of P sorption and desorption. All these highlights that the agricultural soils in UA have a high risk of nutrient loss from agricultural fields to other ecosystems (such as water bodies), but also there is a high risk of P fixation from added fertilizer rendering them unavailable for plant uptakes. Thus, a single fertilizer application program like the one currently in existence in UA allows more P to be lost to the environment and reduces the fertilizer returns and leads to unprofitable and unsustainable farming. Therefore, split fertilizer application whereby the required amount of fertilizer is applied in the given field in more than one application by dividing the amount required into 2 or more. This will ensure all applied plant nutrients (i.e., P and N) from fertilizer to be available for plants uptakes ensuring high crop productivity and less nutrient loss to the environment, thus ensuring environmental quality. Other practice to increase P availability for crop uptake recommended in Usangu agro-ecosystem includes; fertilizer mixing such as ammonium (CAN, SA) with P-fertilizer than application P-fertilizer alone is reported to increase P availability, application of sulphur in neutral and alkaline soils where P is available as Ca-phosphates, application of OM or manure which act as chelating agents that's bind Al and Fe thus preventing formation of Al-and Fe-phosphates, but upon mineralization organic manure release P and other nutrients, application timing where P is applied shortly before planting and banding to crop rows to reduce fixation. In addition, to practice alternate wetting and drying irrigation or intermittent irrigation (wetting and drying) as continuous wetting or excessive moisture reduce P availability and uptake as a result of reduced soil aeration.

**(iii) The use of slow-releasing or coated fertilizers**

As mentioned earlier in this document, 89.68% of the cultivated land in the Usangu agro-ecosystem is covered by paddy rice farming (Kadigi *et al.*, 2003). Where paddy rice irrigation farming is a dominant activity, and the common irrigation system practised in Usangu agro-ecosystem is the flooding irrigation system. Where flooding irrigation system allows water to enter the paddy fields and accumulate (sometimes reaching a water depth of 25 cm as observed in Kapunga irrigation scheme) because there is no control of the amount of water entering the paddy fields, usually there is a constant water movement in the field, and excess water are draining out. The analysis of water draining out from agricultural fields, as determined by this study observed to have higher N and P concentrations, which indicates that there is a high loss of plant nutrients from agricultural fields via surface water drainages. For that reason, it is recommended to use slow-releasing or coated fertilizer which is purposely made to be used in areas with high moisture content. The use of slow-releasing or coated fertilizer under flooding irrigation systems will release plant nutrients slowly, thus ensuring high fertilizer returns and less loss of nutrients (N and P) to the environment.

**(iv) To adopt alternate wetting and drying irrigation pattern rather than continuous flooding**

The alternate wetting and drying irrigation pattern in paddy farming areas help to ensure the applied agrochemicals and fertilizer are used in a particular field, and less is lost to the environment, as the current status in paddy rice farming areas where water is allowed to continuously flow in the field even few days after fertilizer and other agrochemicals application. As pointed out earlier alternate wetting and drying irrigation pattern have been observed to increase crop growth and yield as they enhance better aeration and tillering but also reduce uptake and availability of toxic metals, which could negatively affect the crop growth. Therefore continuous flooding system of irrigation, as commonly practised in Usangu agro-ecosystem, is highly discouraged, especially under this global climate change scenario.

## REFERENCES

- Abail, Z., & Whalen, J. K. (2021). Earthworm contributions to soil nitrogen supply in corn-soybean agroecosystems in Quebec, Canada. *Pedosphere*, *31*(3), 405–412. [https://doi.org/10.1016/S1002-0160\(20\)60086-8](https://doi.org/10.1016/S1002-0160(20)60086-8)
- Abdu, N., Agbenin, J. O., & Buerkert, A. (2011). Geochemical assessment, distribution, and dynamics of trace elements in urban agricultural soils under long-term wastewater irrigation in Kano, northern Nigeria. *Journal of Plant Nutrition and Soil Science*, *174*(3), 447–458. <https://doi.org/10.1002/jpln.201000333>
- Abdullahi, M., Mohammed, S., & Aliu, S. (2014). Analysis of Zr, Pb and Zn in Soil and Cereal Grown Around Birnin Gwari Artisanal Goldmine, Kaduna State-Nigeria. *American Journal of Engineering Research (AJER)*, *03*(12), 134–138.
- Addis, W., & Abebaw, A. (2017). Determination of heavy metal concentration in soils used for cultivation of *Allium sativum* L.(garlic) in East Gojjam Zone, Amhara Region, Ethiopia. *Cogent Chemistry*, *3*(1), 1419422. <https://doi.org/10.1080/23312009.2017.1419422>
- Adhikari, D., Jiang, T., Kawagoe, T., Kai, T., Kubota, K., Araki, K. S., & Kubo, M. (2017). Relationship among phosphorus circulation activity, bacterial biomass, pH, and mineral concentration in agricultural soil. *Microorganisms*, *5*(4). <https://doi.org/10.3390/microorganisms5040079>
- Agrelli, D., Adamo, P., Cirillo, T., Duri, L. G., Duro, I., Fasano, E., Ottaiano, L., Ruggiero, L., Scognamiglio, G., & Fagnano, M. (2017). Soil versus plant as indicators of agroecosystem pollution by potentially toxic elements. *Journal of Plant Nutrition and Soil Science*, *180*(6), 705–719. <https://doi.org/10.1002/jpln.201700050>
- Agrelli, D., Duri, L. G., Fiorentino, N., Cozzolino, E., Fagnano, M., & Adamo, P. (2020). Potentially toxic element availability and risk assessment of cadmium dietary exposure after repeated croppings of *Brassica juncea* in a contaminated agricultural soil. *Agronomy*, *10*(6). <https://doi.org/10.3390/agronomy10060880>
- Akeel, A., & Jahan, A. (2020). Role of cobalt in plants: its stress and alleviation. In *Contaminants in Agriculture* (pp. 339–357). Springer.
- Ali, R. M., Mahoo, H. F., & Resources, N. (2016). Research note: evaluation of irrigation water quality for paddy production at Bumbwisudi Rice Irrigation Scheme, Zanzibar. *Tanzania Journal of Agricultural Sciences*, *15*(2), 114–119.

- Almás, Á. R., & Manoko, M. L. K. (2012). Trace Element Concentrations in Soil, Sediments, and Waters in the Vicinity of Geita Gold Mines and North Mara Gold Mines in Northwest Tanzania. *Soil and Sediment Contamination*, 21(2), 135–159. <https://doi.org/10.1080/15320383.2012.649372>
- Amuri, N., Mhoru, L., Munishi, J. A., Msanya, B. M., Semu, E., & Malley, Z. (2012). *Pedological characteristics and implication on soil fertility of selected soils of Mbeya Region, Tanzania The 3rd RUFORUM Biennial Conference*. <http://www.suaire.suanet.ac.tz:8080/xmlui/bitstream/handle/123456789/73>
- Araújo, P. R. M., Biondi, C. M., do Nascimento, C. W. A., da Silva, F. B. V., Ferreira, T. O., & de Alcântara, S. F. (2022). Geospatial modeling and ecological and human health risk assessments of heavy metals in contaminated mangrove soils. *Marine Pollution Bulletin*, 177(March), 113489. <https://doi.org/10.1016/j.marpolbul.2022.113489>
- Ariga, J., & Heffernan, P. (2012). *Tanzania Fertilizer Assessment*. June, 51. <http://www.ifdc.org/r-d/research/tanzania-fertilizer-assessment>
- Asomaning, S. K., Abekoe, M. K., & Dowuona, G. N. N. (2018). Phosphorus sorption capacity in relation to soil properties in profiles of sandy soils of the Keta sandspit in Ghana. *West African Journal of Applied Ecology*, 26(1), 49–60. <https://doi.org/10.4314/wajae.v26i1>
- Atafar, Z., Mesdaghinia, A., Nouri, J., Homae, M., Yunesian, M., Ahmadimoghaddam, M., & Mahvi, A. H. (2010). Effect of fertilizer application on soil heavy metal concentration. *Environmental Monitoring and Assessment*, 160(1–4), 83–89. <https://doi.org/10.1007/s10661-008-0659-x>
- Awotoye, O. O., Oyedele, D. J., & Anwadike, B. C. (2011). Effects of cow-dung and rock phosphate on heavy metal content in soils and plants. *Journal of Soil Science and Environmental Management*, 2(7), 193–197. <http://www.academicjournals.org/JSSEM>
- Ayuke, F. O., Pulleman, M. M., Vanlauwe, B., de Goede, R. G. M., Six, J., Csuzdi, C., & Brussaard, L. (2011). Agricultural management affects earthworm and termite diversity across humid to semi-arid tropical zones. *Agriculture, Ecosystems and Environment*, 140(1–2), 148–154. <https://doi.org/10.1016/j.agee.2010.11.021>
- Bachmann, S., Uptmoor, R., & Eichler-Löbermann, B. (2016). Phosphorus distribution and availability in untreated and mechanically separated biogas digestates. *Scientia Agricola*, February. <https://doi.org/10.1590/0103-9016-2015-0069>

- Ballabio, C., Panagos, P., Lugato, E., Huang, J. H., Orgiazzi, A., Jones, A., Fernández-Ugalde, O., Borrelli, P., & Montanarella, L. (2018). Copper distribution in European topsoils: An assessment based on LUCAS soil survey. *Science of the Total Environment*, *636*, 282–298. <https://doi.org/10.1016/j.scitotenv.2018.04.268>
- Balmford, A., Green, R., & Phalan, B. (2012). What conservationists need to know about farming. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1739), 2714–2724. <https://doi.org/10.1098/rspb.2012.0515>
- Banzi, F. P., Msaki, P. K., & Mohammed, N. K. (2015). Distribution of Heavy Metals in Soils in the Vicinity of the Proposed Mkuju Uranium Mine in Tanzania. *Environment and Pollution*, *4*(3), 42–50. <https://doi.org/10.5539/ep.v4n3p42>
- Barrow, N. J. (2017). The effects of pH on phosphate uptake from the soil. *Plant and Soil*, *410*(1–2), 401–410. <https://doi.org/10.1007/s11104-016-3008-9>
- Barrow, N. J. (2020). Comparing two theories about the nature of soil phosphate. *European Journal of Soil Science*, *July*, 679–685. <https://doi.org/10.1111/ejss.13027>
- Barrow, N. J., & Debnath, A. (2015). Effect of phosphate status and pH on sulphate sorption and desorption. *European Journal of Soil Science*, *66*(2), 286–297. <https://doi.org/10.1111/ejss.12223>
- Barrow, N. J., & Debnath, A. (2020). Reply to: Navigating limitations and opportunities of soil phosphorus fractionation: a comment on “The soil phosphate fractionation fallacy” by Barrow *et al.* 2020. *Plant and Soil*, *453*(1–2), 595–596. <https://doi.org/10.1007/s11104-020-04574-5>
- Barrow, N. J., Debnath, A., & Sen, A. (2020). Measurement of the effects of pH on phosphate availability. *Plant and Soil*, *454*(1–2), 217–224. <https://doi.org/10.1007/s11104-020-04647-5>
- Barrow, N. J., Debnath, A., & Sen, A. (2021). Effect of pH and prior treatment with phosphate on the rate and amount of reaction of soils with phosphate. *European Journal of Soil Science*, *72*(1), 243–253. <https://doi.org/10.1111/ejss.12968>
- Bationo, A., Waswa, B., Kihara, J., & Kimetu, J. (2005). *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*. <https://doi.org/10.1007/978-1-4020-5760-1>

- Behera, M. D., Borate, S. N., Panda, S. N., Behera, P. R., & Roy, P. S. (2012). Modelling and analyzing the watershed dynamics using Cellular Automata (CA)-Markov model - A geo-information based approach. *Journal of Earth System Science*, *121*(4), 1011–1024. <https://doi.org/10.1007/s12040-012-0207-5>
- Belay, Y. (2015). Integrated soil fertility management for better crop production in Ethiopia. *International Journal of Soil Science*, *10*(1), 1–16. <https://doi.org/10.39223/ijss.2015.1.16>
- Bitaka, M., Kweyunga, C., & Makono, M. (2009). *Levels of heavy metals and cyanide in soil, sediment and water from the vicinity of North Mara Gold Mine in Tarime District, Tanzania.*
- Bolan, N. S., Adriano, D. C., & Naidu, R. (2003). *Role of Phosphorus in ( Im ) mobilization and Bioavailability of Heavy Metals in the Soil – Plant System. Im*, 1–44.
- Borda, T., Celi, L., Bünemann, E. K., Oberson, A., Frossard, E., & Barberis, E. (2014). Fertilization strategies affect phosphorus forms and release from soils and suspended solids. *Journal of Environment Quality*, *43*(3). <https://doi.org/10.2134/jeq2013.11.0436>
- Borggaard, K., Szilas, C., Gimsing, A. L., & Rasmussen, L. H. (2004). Estimation of soil phosphate adsorption capacity by means of a pedotransfer function. *Geoderma*, *118*(1–2), 55–61.
- Borggaard, O. K., Gimsing, A. L., & Strobel, B. W. (2005). *Influence of humic substances on phosphate adsorption by aluminium and iron oxides.* *127*, 270–279. <https://doi.org/10.1016/j.geoderma.2004.12.011>
- Bortoluzzi, E. C., Pérez, C. A. S., Ardisson, J. D., Tiecher, T., & Caner, L. (2015). Occurrence of iron and aluminum sesquioxides and their implications for the P sorption in subtropical soils. *Applied Clay Science*, *104*. <https://doi.org/10.1016/j.clay.2014.11.032>
- Bremner, J. M. (1965). Total nitrogen. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*, *9*, 1149–1178.
- Brian, O. (2021). *Water Research Center - Nitrate Nitrite Nitrogen in Surfacewater and Drinking Water.* <https://water-research.net/index.php/nitrate>
- Busman, L., Lamb, J., Randall, G., Rehm, G., & Schmitt, M. (2009). The nature of phosphorus in soils nitrogen. In *University of Minnesota Extension* (pp. 1–5). <http://www.extension.umn.edu/agriculture/nutrient-management/phosphorus/the-nature-of-phosphorus/>

- Carvalho, F. P. (2015). Agriculture, pesticides, food security and food safety. *Environmental Science & Policy, October*. <https://doi.org/10.1016/j.envsci.2006.08.002>
- CCME. (2007). (Canadian Council of Ministers of the Environment). Canadian soil quality guidelines for the protection of environmental and human health: summary tables. In: Canadian Environmental Quality Guidelines, 1999. Canadian Council of Ministers of the Environment. In *Canadian Council of Ministers of the Environment, 27(2)*, 108. <https://doi.org/10.1177/004947559702700223>
- Chabukdhara, M., & Nema, A. K. (2013). Heavy metals assessment in urban soil around industrial clusters in Ghaziabad, India: Probabilistic health risk approach. *Ecotoxicology and Environmental Safety, 87*, 57–64. <https://doi.org/10.1016/j.ecoenv.2012.08.032>
- Chanda, A., Akhand, A., Das, A., & Hazra, S. (2011). Cr, Pb and Hg Contamination on Agricultural Soil and Paddy Grain after Irrigation Using Metropolitan Sewage Effluent. *Journal of Applied Environmental and Biological Sciences, 1(10)*, 464–469.
- Chaturvedi, R. K., & Sankar, K. (2006). Laboratory manual for the physico-chemical analysis of soil, water and plant. *Wildlife Institute of India, Dehradun, 97*.
- Chibuike, G. U., & Obiora, S. C. (2014). Heavy metal polluted soils: Effect on plants and bioremediation methods. *Applied and Environmental Soil Science, 2014*. <https://doi.org/10.1155/2014/752708>
- Chintala, R., Schumacher, T. E., McDonald, L. M., Clay, D. E., Malo, D. D., Papiernik, S. K., Clay, S. A., & Julson, J. L. (2014). Phosphorus sorption and availability from biochars and soil/biochar mixtures. *Clean - Soil, Air, Water, 42(5)*, 626–634. <https://doi.org/10.1002/clen.201300089>
- Choi, Y. Y. (2011). *International / National Standards for Heavy Metals in Food. October*, 1–13.
- Clover, J. (2003). Food Security in Sub-Saharan Africa. *African Security Review, 12(1)*, 5–15. <https://doi.org/10.1080/10246029.2003.9627566>
- da Silva, F. B. V., do Nascimento, C. W. A., Araújo, P. R. M., da Silva, L. H. V., & da Silva, R. F. (2016). Assessing heavy metal sources in sugarcane Brazilian soils: an approach using multivariate analysis. *Environmental Monitoring and Assessment, 188(8)*. <https://doi.org/10.1007/s10661-016-5409-x>

- Dániel, F., János, S., & Mónika, H. R. (2019). The challenge of feeding the World. *Sustainability*, 2017.
- Daniel, T. C., Sharpley, A. N., & Lemunyon, J. L. (1998). Agricultural phosphorus and eutrophication: A symposium overview. *Journal of Environment Quality*, 27(2), 251. <https://doi.org/10.1017/S0031182007003927>
- De Bolle, S. (2013). *Phosphate saturation and phosphate leaching of acidic sandy soils in Flanders: Analysis and mitigation options*. (Doctoral dissertation, Ghent University).
- De Campos, M., Antonangelo, J. A., van der Zee, S. E. A. T. M., & Alleoni, L. R. F. (2018). Degree of phosphate saturation in highly weathered tropical soils. *Agricultural Water Management*, 206(March 2017), 135–146. <https://doi.org/10.1016/j.agwat.2018.05.001>
- De Smet, J., Hofman, G., Van Meirvenne, M., Vanderdeelen, J., & Baert, L. (1996). Variability of the phosphate saturation degree of the sandy loam soils in west-flanders, Belgium. *Communications in Soil Science & Plant Analysis*, 27(5–8), 1875–1884. <https://doi.org/10.1080/00103629609369675>
- De Villiers, S. (2007). The deteriorating nutrient status of the Berg River, South Africa. *Water SA*, 33(5), 659–664.
- Defarge, N., Spiroux de Vendômois, J., & Séralini, G. E. (2018). Toxicity of formulants and heavy metals in glyphosate-based herbicides and other pesticides. *Toxicology Reports*, 5(October 2017), 156–163. <https://doi.org/10.1016/j.toxrep.2017.12.025>
- Delvaux, D. F., & Hanon, M. (1993). Neotectonics of the Mbeya Area, South West Tanzania. *Museum Royal African Centre.*, 97, 87–97.
- Diatta, J., Waraczewska, Z., Grzebisz, W., Niewiadomska, A., & Tatuśko-Krygier, N. (2020). Eutrophication Induction Via N/P and P/N Ratios Under Controlled Conditions—Effects of Temperature and Water Sources. *Water, Air, and Soil Pollution*, 231(4). <https://doi.org/10.1007/s11270-020-04480-7>
- Doughty, H. W. (1924). Mohr's method for the determination of silver and halogens in other than neutral solutions. *Journal of the American Chemical Society*, 46(12), 2707–2709. <https://doi.org/10.1021/ja01677a014>

- Du Laing, G., De Vos, R., Vandecasteele, B., Lesage, E., Tack, F. M. G., & Verloo, M. G. (2008). Effect of salinity on heavy metal mobility and availability in intertidal sediments of the Scheldt estuary. *Estuarine, Coastal and Shelf Science*, 77(4), 589–602. <https://doi.org/10.1016/j.ecss.2007.10.017>
- Duan, Z., Luo, Y., Wu, Y., Wang, J., Cai, X., Wen, J., & Xu, J. (2021). Heavy metals accumulation and risk assessment in a soil-maize (*Zea mays* L.) system around a zinc-smelting area in southwest China. *Environmental Geochemistry and Health*, 43(12), 4875–4889. <https://doi.org/10.1007/s10653-021-01003-z>
- Ebrahimi, M., Souri, M. K., Mousavi, A., & Sahebani, N. (2021). Biochar and vermicompost improve growth and physiological traits of eggplant (*Solanum melongena* L.) under deficit irrigation. *Chemical and Biological Technologies in Agriculture*, 8(1), 1–14. <https://doi.org/10.1186/s40538-021-00216-9>
- Elisa, M., Kihwele, E., Wolanski, E., & Birkett, C. (2021). Managing wetlands to solve the water crisis in the Katuma River ecosystem, Tanzania. *Ecohydrology and Hydrobiology*, 21, 211–222. <https://doi.org/10.1016/j.ecohyd.2021.02.001>
- Emurotu, J. E., & Onianwa, P. C. (2017). Bioaccumulation of heavy metals in soil and selected food crops cultivated in Kogi State, North Central Nigeria. *Environmental Systems Research*, 1–9. <https://doi.org/10.1186/s40068-017-0098-1>
- Ezeh, A. C., Bongaarts, J., & Mberu, B. (2012). Global population trends and policy options. *The Lancet*, 380(9837), 142–148. [https://doi.org/10.1016/S0140-6736\(12\)60696-5](https://doi.org/10.1016/S0140-6736(12)60696-5)
- Fagnano, M., Agrelli, D., Pascale, A., Adamo, P., Fiorentino, N., Rocco, C., Pepe, O., & Ventrino, V. (2020). Copper accumulation in agricultural soils: Risks for the food chain and soil microbial populations. *Science of the Total Environment*, 734, 139434. <https://doi.org/10.1016/j.scitotenv.2020.139434>
- Fanny, V. (2019). *The state of Lake Rukwa-Katavi Landscape*.
- FAO. (1985). *Water Quality for Agriculture*.
- FAO. (2006). World Reference Base for Soil Resources. *Encyclopedia of Soil Science, Second Edition*. <https://doi.org/10.1201/noe0849338304.ch410>
- FAO. (2014). World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. In *World Soil Resources Reports No. 106*.

- FAO. (2015). How to Feed the World in 2050. *Synthesis Report*, 42(2), 128–137. <https://doi.org/10.3146/0095-3679-42.2.128>
- FAO. (2021). *Water quality for agriculture*. <http://www.fao.org/3/t0234e/t0234e06.htm>
- FBD. (2007). *Eastern Arc Mountains Strategy Thematic Strategy: Mechanism for Payments for Water Environmental Services, Rufiji River Basin, Tanzania*. <http://www.tfcg.org/wp-content/uploads/2018/05/CMEAMF-IEC-strategy-report-2006.pdf>
- Fergusson, J., & Ryan, D. (1984). the Elemental Composition of Street Dust From Large. *The Science of the Total Environment*, 34, 101–116.
- Ferreira-Baptista, L., & De Miguel, E. (2005). Geochemistry and risk assessment of street dust in Luanda, Angola: A tropical urban environment. *Atmospheric Environment*, 39(25), 4501–4512. <https://doi.org/10.1016/j.atmosenv.2005.03.026>
- Fink, J. R., Inda, A. V., Tiecher, T., & Barrón, V. (2016). Iron oxides and organic matter on soil phosphorus availability. *Ciencia e Agrotecnologia*, 40(4), 369–379. <https://doi.org/10.1590/1413-70542016404023016>
- Fipps, G. (2003). Irrigation water quality standards and salinity management strategies. *Texas A&M Agrilife Extension*, 4(03), 1–18.
- Fischer, P., Pöthig, R., & Venohr, M. (2017). The degree of phosphorus saturation of agricultural soils in Germany: Current and future risk of diffuse P loss and implications for soil P management in Europe. *Science of the Total Environment*, 599–600. <https://doi.org/10.1016/j.scitotenv.2017.03.143>
- Fortune, S., Lu, J., Addiscott, T. M., & Brookes, P. C. (2005). Assessment of phosphorus leaching losses from arable land. *Plant and Soil*, 269(1–2), 99–108. <https://doi.org/10.1007/s11104-004-1659-4>
- Fox, B. (2004). *An Overview of the Usangu Catchment, Ihefu Wetland, & Great Ruaha River Ecosystem Environmental disaster*. March, pp.1-15.
- Freese, D., Van der Zee, S., & Van Riemsdijk, W. H. (1992). Comparison of different models for phosphate sorption as a function of the iron and aluminium oxides of soils. *Journal of Soil Science*, 43(4), 729–738.

- Funakawa, S., Yoshida, H., Watanabe, T., Sugihara, S., Kilasara, M., & Kosaki, T. (2012). Soil Fertility Status and Its Determining Factors in Tanzania. In *Soil Health and Land Use Management*. InTech. <https://doi.org/10.5772/29199>
- Gashi, F., Frančišković-Bilinski, S., Bilinski, H., Rexhepi, A., & Robaj, A. (2017). Assessing the distribution of trace elements in water from Batllava Lake (Kosovo). *Sustainable Water Resources Management*, 3(1), 10. <https://doi.org/10.1007/s40899-017-0077-8>
- Gichangi, E. M., Mnkeni, P. N. S., & Muchaonyerwa, P. (2008). Phosphate sorption characteristics and external P requirements of selected South African Soils. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 109(2), 139–149.
- Gikuma-Njuru, P., Rutagemwa, D. K., Mugidde, R., Hecky, R. E., Mwebaza-Ndawula, L., Mwirigi, P. M., Abuodha, J. O. Z., K., W. R., Matovu, A., & Kinobe, J. (2017a). CHAPTER 6 Eutrophication of the Lake Victoria Ecosystem. *Lake Victoria Environment Report*, 81–102.
- Gikuma-Njuru, P., Rutagemwa, D. K., Mugidde, R., Hecky, R. E., Mwebaza-Ndawula, L., Mwirigi, P. M., Abuodha, J. O. Z., K., W. R., Matovu, A., & Kinobe, J. (2017b). *Eutrophication of Lake Victoria, Kenya : lessons for Water quality. 1985(Ochumba 1990)*.
- Gobler, C. J., Heil, C. A., Kudela, R., Parsons, M. L., Jack, J. E., Townsend, D. W., Trainer, V. L., & Vargo, G. A. (2008). Harmful algal blooms and eutrophication: Examining linkages from selected coastal regions of the United States. *Harmful Algae*, 8(1), 39–53. <https://doi.org/10.1016/j.hal.2008.08.017>.
- Goncalves, A. C., Nacke, H., Schwantes, D., & Coelho, G. F. (2014). Heavy Metal Contamination in Brazilian Agricultural Soils due to Application of Fertilizers. *Environmental Risk Assessment of Soil Contamination*. <https://doi.org/10.5772/57268>
- Gonzalez-Rodriguez, S., & Fernandez-Marcos, M. L. (2018). Phosphate sorption and desorption by two contrasting volcanic soils of equatorial Africa. *PeerJ*, 2018(10), 1–14. <https://doi.org/10.7717/peerj.5820>
- Gujre, N., Rangan, L., & Mitra, S. (2021). Occurrence, geochemical fraction, ecological and health risk assessment of cadmium, copper and nickel in soils contaminated with municipal solid wastes. *Chemosphere*, 271, 129-573. <https://doi.org/10.1016/j.chemosphere.2021.129573>

- Guo, C., Chen, Y., Xia, W., Qu, X., Yuan, H., Xie, S., & Lin, L. S. (2020). Eutrophication and heavy metal pollution patterns in the water supplying lakes of China's south-to-north water diversion project. *Science of the Total Environment*, 711, 134543. <https://doi.org/10.1016/j.scitotenv.2019.134543>
- Guo, M. (2009). Soil Sampling and Methods of Analysis. *Journal of Environmental Quality*, 38(1), 375–375. <https://doi.org/10.2134/jeq2008.0018br>
- Guo, Q., Wang, Y., Qian, J., Zhang, B., Hua, M., Liu, C., & Pan, B. (2021). Enhanced production of methane in anaerobic water treatment as mediated by the immobilized fungi. *Water Research*, 190, 116-761. <https://doi.org/10.1016/j.watres.2020.116761>
- Guppy, C. N., Menzies, N. W., Moody, P. W., & Blamey, F. P. C. (2005). Competitive sorption reactions between phosphorus and organic matter in soil: a review. *Soil Research*, 43(2), 189–202.
- Hakanson, L. (1980). An ecological risk index for aquatic pollution control: a sedimentological approach. *Water Research*, 14(8), 975–1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
- Heidari, M., Darijani, T., & Alipour, V. (2021). Heavy metal pollution of road dust in a city and its highly polluted suburb; quantitative source apportionment and source-specific ecological and health risk assessment. *Chemosphere*, 273, 129-656. <https://doi.org/10.1016/j.chemosphere.2021.129656>
- Henryson, K., Sundberg, C., Kätterer, T., & Hansson, P. A. (2018). Accounting for long-term soil fertility effects when assessing the climate impact of crop cultivation. *Agricultural Systems*, 164(July 2017), 185–192. <https://doi.org/10.1016/j.agry.2018.03.001>
- Herman, A., & Kihampa, C. (2015). Heavy Metals Contamination in Soils and Water in the Vicinity of Small Scale Gold Mines at Londoni and Sambaru, Singida Region, Tanzania. *International Journal of Environmental Monitoring and Analysis*, 3(6), 397. <https://doi.org/10.11648/j.ijema.20150306.13>
- Hongthanat, N. (2010). *Phosphorus sorption-desorption of soils and sediments in the Rathbun Lake watershed*. 71. <http://lib.dr.iastate.edu/etd/11558>

- Hooda, P. S., Rendell, A. R., Edwards, A. C., Withers, P. J. A., Aitken, M. N., & Truesdale, V. W. (2000). Relating Soil Phosphorus Indices to Potential Phosphorus Release to Water. *Journal of Environment Quality*, 29(4), 1166. <https://doi.org/10.2134/jeq2000.00472425002900040018x>
- Horneck, D., Sullivan, D., Owen, J., & Hart, J. (1999). Soil Test Interpretation Guide. *Communications, Experiment Station State, Oregon Rehabilitation*, 3, 1–8. <https://doi.org/10.1017/CBO9781107415324.004>
- Hu, J., Lesseur, C., Miao, Y., Manservigi, F., & Panzacchi, S. (2021). Low - dose exposure of glyphosate - based herbicides disrupt the urine metabolome and its interaction with gut microbiota. *Scientific Reports*, 1–10. <https://doi.org/10.1038/s41598-021-82552-2>
- Hussain, M. M., Hina, A., Saeed, A., Sabahat, S., Jannat, F. T., & Aslam, M. (2017). Impact of heavy metals on plants and animals in relation to sewage water. *Science, Technology and Development*, 36(4), 215–226. <https://doi.org/10.3923/std.2017.215.226>
- Ingenbleek, L., Verger, P., Gimou, M., Adegboye, A., Adebayo, S. B., Hossou, S. E., Lopes-pereira, L., Hu, R., Sulyok, M., Krska, R., Marchand, P., Bizec, B. Le, Eyangoh, S., Kamanzi, J., Ouattara, B., Merten, C., Lipp, M., Clarke, R., & Leblanc, J. (2020). Human dietary exposure to chemicals in Sub-Saharan Africa: safety assessment through a total diet study. *The Lancet Planetary Health*, 4(7), 292–300. [https://doi.org/10.1016/S2542-5196\(20\)30104-2](https://doi.org/10.1016/S2542-5196(20)30104-2)
- Isdory, D., Massawe, B. H., & Msanya, B. (2021). Predicting Soil E<sub>Ce</sub> Based on Values of EC<sub>1:2.5</sub> as an Indicator of Soil Salinity at Magozi Irrigation Scheme, Iringa, Tanzania. *Tanzania Journal of Agricultural Sciences*, 20(1), 63–71.
- Isham, J. (2005). The Effect of Social Capital on Technology Adoption: Evidence from Rural Tanzania. *Journal of African Economies*, 1–31. <https://doi.org/10.2139/ssrn.260053>
- Jalali, M. (2017). Minerals control phosphorus solubility in long-term-cultivated calcareous soils. *Soil Research*, 55(2), 182–190. <https://doi.org/10.1071/SR16057>
- Jepson, P. C., Guzy, M., Blaustein, K., Sow, M., Sarr, M., Mineau, P., & Kegley, S. (2014). Measuring pesticide ecological and health risks in West African agriculture to establish an enabling environment for sustainable intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1639). <https://doi.org/10.1098/rstb.2013.0491>

- Jian, L., Hongbin, L., Ruliang, L., MG Mostofa, A., Limei, Z., Haiming, L., Hongyuan, W., Xubo, Z., Yitao, Z., Ying, Z., & Xiaodong, D. (2016). Water Quality in Irrigated Paddy Systems. *Intech, i(tourism)*, 13. <https://doi.org/http://dx.doi.org/10.5772/57353>
- Kadigi, M., Kashaingili, R., Mdoe, J., & Ntengua, S. (2003). *The Economics of Irrigated Paddy in Usangu Basin in Tanzania*. 3–8.
- Kamota, A., Muchaonyerwa, P., & Mnkeni, P. N. S. (2012). Effects of transgenic maize expressing the Cry1Ab protein (event MON810) on locally adapted earthworms in a sandy loam soil in the Central Eastern Cape, South Africa. *African Journal of Biotechnology*, 11(85), 15168–15170. <https://doi.org/10.5897/AJB12.2021>
- Kamprath, E. J. (1970). Exchangeable Aluminum As a Criterion for Liming Leached Mineral Soils. *Soil Science Society of America Journal*, 34(2), 252–254. <https://doi.org/10.2136/sssaj1970.03615995003400020022x>
- Kangalawe, R. Y., Mwamfupe, D., & Mbonile, M. (2007). Land Management Systems and Their Environmental Impacts in the Usangu Plains, Tanzania. *Journal of the Geographical Association of Tanzania*, 32(2007), 15–32.
- Karlsson, I., & Messing, I. (1980). *A reconnaissance soil survey in parts of Mbeya region in Tanzania*.
- Kashaigili, J., Matthew, P., Henry, M., Mahoo, F., A, B., Mbilinyi, B., Tumbo, S., & I. (2006). Use of a hydrological model for environmental management of the Usangu Wetlands, Tanzania. In *IWMI Research Report* (Issue 104).
- Kashenge-Killenga, S., Meliyo, J., Urassa, G., & Kongo, V. (2016). Extent of salt-affected soils and their effects in irrigated and lowland rain-fed rice growing areas of southwestern Tanzania. In *Climate Change and Multi-Dimensional Sustainability in African Agriculture* (pp. 97–126). Springer.
- Katambara, Z., Mng'ong'o, M., Chambi, C., & Malley, Z. (2016). Characteristics of rice produced under direct and indirect SRI practices in Chimala Area in Mbarali District Tanzania. *Journal of Agriculture and Sustainability*, 9(1), 15–30.
- Kelepertzis, E. (2014). Accumulation of heavy metals in agricultural soils of Mediterranean: Insights from Argolida basin, Peloponnese, Greece. *Geoderma*, 221–222, 82–90. <https://doi.org/10.1016/j.geoderma.2014.01.007>

- Kersten, M., & Forstner, U. (1986). Chemical fractionation of heavy metals in anoxic estuarine and coastal sediments. *Water Science and Technology*, *18*(4–5), 121–130. <https://doi.org/10.2166/wst.1986.0187>
- Khan, F. A., & Ansari, A. A. (2005). Eutrophication: An ecological vision. *Botanical Review*, *71*(4), 449–482. [https://doi.org/10.1663/0006-8101\(2005\)071\[0449:EAEV\]2.0.CO;2](https://doi.org/10.1663/0006-8101(2005)071[0449:EAEV]2.0.CO;2)
- Khani, M. N., Mobin, M., Abbas, Z. K., & Alamri, S. A. (2017). Fertilizers and Their Contaminants in Soils, Surface and Groundwater. In *Encyclopedia of the Anthropocene* (Issue April 2018). Elsevier Inc. <https://doi.org/10.1016/b978-0-12-809665-9.09888-8>
- Kibassa, D., Kimaro, A., & Shemdoe, R. (2013). Heavy metals concentrations in selected areas used for urban agriculture in Dar es Salaam, Tanzania. *Scientific Research and Essays*, *8*(27), 1296–1303. <https://doi.org/10.5897/SRE2013.5404>
- Kihwele, E., Muse, E., Magomba, E., Mnaya, B., Nassoro, A., Banga, P., Murashani, E., Irmamasita, D., Kiwango, H., Birkett, C., & Wolanski, E. (2018). Restoring the perennial Great Ruaha River using ecohydrology, engineering and governance methods in Tanzania. *Ecohydrology and Hydrobiology*, *18*(2), 120–129. <https://doi.org/10.1016/j.ecohyd.2017.10.008>
- Kimaro, J. (2019). A Review on Managing Agroecosystems for Improved Water Use Efficiency in the Face of Changing Climate in Tanzania. *Advances in Meteorology*, *2019*. <https://doi.org/10.1155/2019/9178136>
- Kinuthia, G. K., Ngure, V., Beti, D., Lugalia, R., Wangila, A., & Kamau, L. (2020). Levels of heavy metals in wastewater and soil samples from open drainage channels in Nairobi, Kenya: community health implication. *Scientific Reports*, *10*(1), 1–13. <https://doi.org/10.1038/s41598-020-65359-5>
- Kiss, T. B. W., Chen, X., Ponting, J., Sizmur, T., & Hodson, M. E. (2021). Dual stresses of flooding and agricultural land use reduce earthworm populations more than the individual stressors. *Science of the Total Environment*, *754*, 142–202. <https://doi.org/10.1016/j.scitotenv.2020.142102>
- Kitula, A. G. N. (2006). The environmental and socio-economic impacts of mining on local livelihoods in Tanzania: A case study of Geita District. *Journal of Cleaner Production*, *14*(3–4), 405–414. <https://doi.org/10.1016/j.jclepro.2004.01.012>

- Kitundu, K. M., & Mrema, J. p. (2006). The Status of Zn, Cu, and Fe in the Soils and Tea-Leaves of Kibena -Tea Estates-Njombe, Tanzania. *Tanzania Journal of Science*, 7(1), 34–41.
- Kleinman, P. J. A. (2017). The Persistent Environmental Relevance of Soil Phosphorus Sorption Saturation. *Current Pollution Reports*, 3(2), 141–150. <https://doi.org/10.1007/s40726-017-0058-4>
- Kleinman, P. J. A., & Sharpley, A. N. (2002). Estimating soil phosphorus sorption saturation from Mehlich-3 data. *Communications in Soil Science and Plant Analysis*, 33(11–12), 1825–1839. <https://doi.org/10.1081/CSS-120004825>
- Kleinman, P. J. A., Sharpley, A. N., Withers, P. J. A., Bergström, L., Johnson, L. T., & Doody, D. G. (2015). Implementing agricultural phosphorus science and management to combat eutrophication. *Ambio*, 44(2), 297–310. <https://doi.org/10.1007/s13280-015-0631-2>
- Koleleni, Y. I., & Mbike, S. A. (2018). Analysis of Heavy Metals in Soil and Maize Grown around Namungo Gold Mine in Ruangwa District, Lindi Region in Tanzania Using X-ray Fluorescence. *Chemical Science International Journal*, 24(4), 1–18. <https://doi.org/10.9734/csji/2018/44976>
- Korkmaz, D. (2011). Determination of Chloride Ion Concentration by Titration (Mohr's Method). *University of Cantearbury*, 1–2.
- Krupa, M., Tate, K. W., van Kessel, C., Sarwar, N., & Linqvist, B. A. (2011). Water quality in rice-growing watersheds in a Mediterranean climate. *Agriculture, Ecosystems and Environment*, 144(1), 290–301. <https://doi.org/10.1016/j.agee.2011.09.004>
- Lema, M. W., Ijumba, J. N., Njau, K. N., & Ndakidemi, P. A. (2014). Environmental Contamination By Radionuclides And Heavy Metals Through The Application Of Phosphate Rocks During Farming And Mathematical Modeling Of Their Impacts To The Ecosystem. *International Journal of Engineering Research and General Science*, 2(4), 852–863.
- Lema, M. W., & Mseli, Z. H. (2017). *Assessment of Soil Pollution ( Heavy Metal ) from Small Scale Gold Mining Activities: A Case of*. 4(1), 1–5.
- Li, L., He, J., Gan, Z., & Yang, P. (2021). Occurrence and fate of antibiotics and heavy metals in sewage treatment plants and risk assessment of reclaimed water in Chengdu, China. *Chemosphere*, 272, 129730. <https://doi.org/10.1016/j.chemosphere.2021.129730>

- Li, Z., Huo, J., & Bricker, J. D. (2019). Ecological risk assessment for eutrophication and heavy metal pollution of Suyahu Reservoir sediments. *Biotechnology and Biotechnological Equipment*, *33*(1), 1053–1062. <https://doi.org/10.1080/13102818.2019.1638833>
- Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA Soil Test for Zinc, Iron, Manganese, and Copper. *Soil Science Society of America Journal*, *42*(3), 421–428. <https://doi.org/10.2136/sssaj1978.03615995004200030009x>
- Liu, Z., Zhang, Q., Han, T., Ding, Y., Sun, J., Wang, F., & Zhu, C. (2015). Heavy metal pollution in a soil-rice system in the Yangtze river region of China. *International Journal of Environmental Research and Public Health*, *13*(1). <https://doi.org/10.3390/ijerph13010063>
- Lü, Q., Xiao, Q., Wang, Y., Wen, H., Han, B., Zheng, X., & Lin, R. (2021). Risk assessment and hotspots identification of heavy metals in rice: A case study in Longyan of Fujian province, China. *Chemosphere*, *270*, 128626. <https://doi.org/10.1016/j.chemosphere.2020.128626>
- Lugwisha, E. H. (2016). Heavy Metal Levels in Soil, Tomatoes and Selected Vegetables from Morogoro Region, Tanzania. *International Journal of Environmental Monitoring and Analysis*, *4*(3), 82. <https://doi.org/10.11648/j.ijema.20160403.13>
- Machibya, M., & Mdemu, M. (2005). Comparison assessment of water use and damage between modern and traditional rice irrigation schemes: Case of Usangu basin, Tanzania. *International Journal of Environmental Research and Public Health*, *2*(2), 335–342. <https://doi.org/10.3390/ijerph2005020020>
- Machiwa, J. F. (2010). Heavy Metal Levels in Paddy Soils and Rice (*Oryza sativa* (L)) from Wetlands of Lake Victoria Basin, Tanzania. *Tanzania Journal of Science*, *L*.
- Magnone, D., Niasar, V. J., Bouwman, A. F., Beusen, A. H. W., van der Zee, S. E. A. T. M., & Sattari, S. Z. (2019). Soil Chemistry Aspects of Predicting Future Phosphorus Requirements in Sub-Saharan Africa. *Journal of Advances in Modeling Earth Systems*, *11*(1), 327–337. <https://doi.org/10.1029/2018MS001367>
- Mahugija, J. A. M., & Sheikh, H. M. (2018). Status of Selected Heavy Metals Dispersion from Top Soil in and Around Automobile Workshop Areas in Zanzibar Municipality, Tanzania. *Tanzania Journal of Science*, *44*(1), 12–23.

- Malidareh, H. B., Mahvi, A. H., Yunesian, M., Alimohammadi, M., & Nazmara, S. (2014). Admium, lead and arsenic content in polished white rice (*Oryza sativa* L.) In Ghaemshahr city (North of Iran). *Middle - East Journal of Scientific Research*, 20(12), 1709–1714. <https://doi.org/10.5829/idosi.mejsr.2014.20.12.13632>
- Mallarino, A. P., Sawyer, J. E., & Barnhart, S. K. (2013). *A general guide for crop nutrient and limestone recommendations in Iowa. Iowa State University Extension. Circular. PM 1688 (revised). October, 12.*
- Malley, Z., Hart, A., Buck, L., Mwambene, P. L., Katambara, Z., Mng'ong'o, M., & Chambi, C. (2017). Integrated agricultural landscape management: Case study on inclusive innovation processes, monitoring and evaluation in the Mbeya Region, Tanzania. *Outlook on Agriculture*, 46(2), 146–153. <https://doi.org/10.1177/0030727017709393>
- Malley, Z., Taeb, M., Matsumoto, T., & Takeya, H. (2007). Environmental change and vulnerability in the Usangu plain, southwestern Tanzania: Implications for sustainable development. *International Journal of Sustainable Development and World Ecology*, 14(2), 145–159. <https://doi.org/10.1080/13504500709469715>
- Malsiu, A., Shehu, I., Stafilov, T., & Faiku, F. (2020). Assessment of Heavy Metal Concentrations with Fractionation Method in Sediments and Waters of the Badovci Lake (Kosovo). *Journal of Environmental and Public Health*, 2020. <https://doi.org/10.1155/2020/3098594>
- Malunguja, G. K., & Devi, A. (2022). Quantitative Assessment and Predicting the Effects of Soil Pollutants on Herbaceous Biomass Production in Reserved Forests. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*. <https://doi.org/10.1007/s40011-021-01325-z>
- Malunguja, G. K., Thakur, B., & Devi, A. (2022). Heavy Metal Contamination of Forest Soils by Vehicular Emissions: Ecological Risks and Effects on Tree Productivity. In *Environmental Processes*. Springer International Publishing. <https://doi.org/10.1007/s40710-022-00567-x>
- Marchese, M., Tuttobene, R., Restuccia, A., Longo, A. M. G., Mauromicale, G., & Restuccia, G. (2008). Effects of electrical conductivity of irrigation water on the growth and production of *Solanum lycopersicum* L. var. cerasiforme grown in greenhouse. *Options Mediterraneennes*, 315(March 2016), 311–315.

- Margenot, A. J., Singh, B. R., Rao, I. M., & Sommer, R. (2016). *Phosphorus Fertilization and Management in Soils of Sub-Saharan Africa* (Issue November, pp. 151–208). <https://doi.org/10.1201/9781315372327-9>
- Mataba, G. R., Verhaert, V., Blust, R., & Bervoets, L. (2016). Distribution of trace elements in the aquatic ecosystem of the Thigithe river and the fish *Labeo victorinus* in Tanzania and possible risks for human consumption. *Science of the Total Environment*, 547(2016), 48–59. <https://doi.org/10.1016/j.scitotenv.2015.12.123>
- Mathew, M. M., Majule, A. E., Marchant, R., & Sinclair, F. (2016). Variability of Soil Micronutrients Concentration along the Slopes of Mount Kilimanjaro, Tanzania. *Applied and Environmental Soil Science*, 2016. <https://doi.org/10.1155/2016/9814316>
- Matowo, N. S., Tanner, M., Munhenga, G., Mapua, S. A., Finda, M., Utzinger, J., Ngowi, V., & Okumu, F. O. (2020). Patterns of pesticide usage in agriculture in rural Tanzania call for integrating agricultural and public health practices in managing insecticide-resistance in malaria vectors. *Malaria Journal*, 19(1), 1–16. <https://doi.org/10.1186/s12936-020-03331-4>
- Mcinga, S., Manyevere, A., & Mnkeni, P. (2021). Earthworm diversity and density as affected by soil and climatic factors in Raymond Mhlaba municipality, Eastern Cape province, South Africa. *South African Journal of Plant and Soil*, 38(1), 19–26. <https://doi.org/10.1080/02571862.2020.1822453>
- Mclean, J. E., & Bledsoe, B. E. (1992). Ground Water Issue Behavior of Metals in Soils. *Director*, 1–25. <https://doi.org/10.1056/NEJMoa030660>
- McLeod, S. (1973). Studies on wet oxidation procedures for the determination of organic carbon in soils. *Notes on Soil Techniques*, 73–79.
- Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, 731847469, 37–41. <https://doi.org/10.1167/iavs.11-7364>
- Meliyo, J. L., Kashenge-Killenga, S., Victor, K. M., Mfupe, B., Hiza, S., Kihupi, A. L., Boman, B. J., & Dick, W. (2016). Evaluation of Salt Affected Soils for Rice (*Oryza Sativa*) Production in Ndungu Irrigation Scheme Same District, Tanzania. *Sustainable Agriculture Research*, 6(1), 24. <https://doi.org/10.5539/sar.v6n1p24>

- Meliyo, J., Massawe, B., Brabers, L., Msanya, B., Kimaro, D., Mulungu, L., Kihupi, N., Deckers, J., Gulinck, H., & Leirs, H. (2015). Status and Variability of Soil Micronutrients with Landforms in the Plague Focus of Western Usambara Mountains, Tanzania. *International Journal of Plant & Soil Science*, 4(4), 389–403. <https://doi.org/10.9734/ijpss/2015/13717>
- Mhoro, L., & Anthony, J. (2015). Growth and yield responses of rice, wheat and beans to Zn and Cu fertilizers in soils of Mbeya region, Tanzania. *International Journal of Agricultural Policy and Research*, 3(November), 402–411. <https://doi.org/10.15739/IJAPR.067>
- Mng'ong'o, M., Munishi, L. K., Blake, W., Comber, S., Hutchinson, T. H., & Ndakidemi, P. A. (2021). Soil fertility and land sustainability in Usangu Basin-Tanzania. *Heliyon*, 7(8), e07745. <https://doi.org/10.1016/j.heliyon.2021.e07745>
- Mng'ong'o, M., Munishi, L. K., Blake, W., Ndakidemi, P. A., Comber, S., & Hutchinson, T. H. (2021). Characterization of soil phosphate status, sorption and saturation in paddy wetlands in usangu basin-Tanzania. *Chemosphere*, 278, 130466. <https://doi.org/10.1016/j.chemosphere.2021.130466>
- Mng'ong'o, M., Munishi, L. K., Comber, S., Ndakidemi, P. A., Blake, W., & Hutchinson, T. H. (2021). Land use patterns influence the distribution of potentially toxic elements in soils of the Usangu Basin, Tanzania. *Chemosphere*, 284(July), 131410. <https://doi.org/10.1016/j.chemosphere.2021.131410>
- Mng'ong'o, M., Munishi, L. K., Ndakidemi, P. A., Blake, W., Comber, S., & Hutchinson, T. H. (2021a). Accumulation and bioconcentration of heavy metals in two phases from agricultural soil to plants in Usangu agroecosystem-Tanzania. *Heliyon*, 7(7), e07514. <https://doi.org/10.1016/j.heliyon.2021.e07514>
- Mng'ong'o, M., Munishi, L. K., Ndakidemi, P. A., Blake, W., Comber, S., & Hutchinson, T. H. (2021b). Toxic metals in East African agro-ecosystems: Key risks for sustainable food production. *Journal of Environmental Management*, 294(May), 112973. <https://doi.org/10.1016/j.jenvman.2021.112973>
- Mongi, R., Chove, L., & Sciences, C. (2020). Heavy Metal Contamination in Cocoyam Crops and Soils in Countries around the Lake Victoria Basin (Tanzania, Uganda and Kenya). *Tanzania Journal of Agricultural Sciences*, 19(2), 148–160.

- Moss, B. (2008). Water pollution by agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), 659–666. <https://doi.org/10.1098/rstb.2007.2176>
- Mowo, J., Floor, J., Kaihura, F. B. S., & Magoggo, J. P. (1993). *Review of Fertilizer Recommendations in Tanzania. Part 2, Revised Fertiliser Recommendations for Tanzania. Soil Fertility Report No. F6.* (pp. 1–71). [http://library.wur.nl/isric/fulltext/isricu\\_i13557\\_001.pdf](http://library.wur.nl/isric/fulltext/isricu_i13557_001.pdf)
- Mowo, J., Janssen, B. H., Oenema, O., German, L. A., Mrema, J. P., & Shemdoe, R. S. (2006). Soil fertility evaluation and management by smallholder farmer communities in northern Tanzania. *Agriculture, Ecosystems and Environment*, 116(1–2), 47–59. <https://doi.org/10.1016/j.agee.2006.03.021>
- Mshana, J. G. (2015). *Mercury and Lead Contamination in Three Fish Species and Sediments from Lake Rukwa and Catchment Areas in Tanzania.* 5(8).
- Mtahiko, M. G. G., Gereta, E., Kajuni, A. R., Chiombola, E. A. T., Ng’umbi, G. Z., Coppolillo, P., & Wolanski, E. (2006). Towards an ecohydrology-based restoration of the Usangu wetlands and the Great Ruaha River, Tanzania. *Wetlands Ecology and Management*, 14(6), 489–503. <https://doi.org/10.1007/s11273-006-9002-x>
- Muindi, E., Mrema, J., Semu, E., Mtakwa, P., Gachene, C., & Njogu, M. (2015). Phosphorus Adsorption and Its Relation with Soil Properties in Acid Soils of Western Kenya. *International Journal of Plant & Soil Science*, 4(3), 203–211. <https://doi.org/10.9734/ijpss/2015/13037>
- Mungai, T. M., Owino, A. A., Makokha, V. A., Gao, Y., Yan, X., & Wang, J. (2016). Occurrences and toxicological risk assessment of eight heavy metals in agricultural soils from Kenya, Eastern Africa. *Environmental Science and Pollution Research*, 23(18), 18533–18541. <https://doi.org/10.1007/s11356-016-7042-1>
- Murphy, J., & Riley, J. P. (1962). Determination Single Solution Method For The In Natural Waters. *Analytica Chimica Act*, 27, 31–36.
- Mutayoba, E., Kashaigili, J. J., Kahimba, F. C., Mbungu, W., & Chilagane, N. A. (2018a). Assessing the Impacts of Land Use and Land Cover Changes on Hydrology of the Mbarali River Sub-Catchment. The Case of Upper Great Ruaha Sub-Basin, Tanzania. *Engineering*, 10(09), 616–635. <https://doi.org/10.4236/eng.2018.109045>

- Mutayoba, E., Kashaigili, J. J., Kahimba, F. C., Mbungu, W., & Chilagane, N. A. (2018b). Assessment of the Impacts of Climate Change on Hydrological Characteristics of the Mbarali River Sub Catchment Using High Resolution Climate Simulations from CORDEX Regional Climate Models. *Applied Physics Research*, *10*(5), 61. <https://doi.org/10.5539/apr.v10n5p61>
- Mwegoha, W. J. S., & Kihampa, C. (2010). Heavy metal contamination in agricultural soils and water in Dar es Salaam city, Tanzania. *African Journal of Environmental Science and Technology*, *4*(11), 763–769. <http://www.academicjournals.org/AJEST>
- Nadeem, M., & Saeed, M. (2013). Assessment of heavy metals and aflatoxin levels in export quality Indica rice cultivars with different milling fractions. *African Journal of Agricultural Research*, *8*(25), 3236–3244. <https://doi.org/10.5897/AJAR2013.6925>
- Nagajyoti, P. C., Lee, K. D., & Sreekanth, T. V. M. (2010). Heavy metals, occurrence and toxicity for plants: A review. *Environmental Chemistry Letters*, *8*(3), 199–216. <https://doi.org/10.1007/s10311-010-0297-8>
- Naidu, R., & Bolan, N. S. (2008). Contaminant Chemistry in Soils: Key Concepts and Bioavailability. *Developments in Soil Science*, *32*(1992), 9–37.
- Najarjan, A., & Souri, M. K. (2020). Influence of sugar cane compost as potting media on vegetative growth, and some biochemical parameters of *Pelargonium × hortorum*. *Journal of Plant Nutrition*, *43*(17), 2680–2684. <https://doi.org/10.1080/01904167.2020.1783305>
- Nájera, F., Tapia, Y., Baginsky, C., Figueroa, V., Cabeza, R., & Salazar, O. (2015). Evaluation of soil fertility and fertilisation practices for irrigated maize (*Zea mays* L.) under mediterranean conditions in central Chile. *Journal of Soil Science and Plant Nutrition*, *15*(1), 84–97. <https://doi.org/10.4067/S0718-95162015005000008>
- Nasukawa, H., Tajima, R., Muacha, B. I. J., Filomena Pereira, M. C., Naruo, K., Nakamura, S., Fukuda, M., Ito, T., & Homma, K. (2019). Analyzing soil-available phosphorus by the Mehlich-3 extraction method to recommend a phosphorus fertilizer application rate for maize production in northern Mozambique. *Plant Production Science*, *22*(2), 211–214. <https://doi.org/10.1080/1343943X.2018.1547649>

- Ndakidemi, P. A., & Semoka, J. M. R. (2006). Soil fertility survey in Western Usambara Mountains, Northern Tanzania. *Pedosphere*, *16*(2), 237–244. [https://doi.org/10.1016/S1002-0160\(06\)60049-0](https://doi.org/10.1016/S1002-0160(06)60049-0)
- Ndungu, A. W., Yan, X., Makokha, V. A., Githaiga, K. B., & Wang, J. (2019). Occurrence and risk assessment of heavy metals and organochlorine pesticides in surface soils, Central Kenya. *Journal of Environmental Health Science and Engineering*, *17*(1), 63–73. <https://doi.org/10.1007/s40201-018-00326-x>
- Neina, D. (2019). The Role of Soil pH in Plant Nutrition and Soil Remediation. *Applied and Environmental Soil Science*, *2019*(3). <https://doi.org/10.1155/2019/5794869>
- Nelson, D. W., & Sommers, L. E. (1980). Total Nitrogen Analysis of Soil and Plant Tissues. *Journal of AOAC International*, *63*(4), 770–778. <https://doi.org/10.1093/jaoac/63.4.770>
- Némery, J., & Garnier, J. (2016). Biogeochemistry: The fate of phosphorus. *Nature Geoscience*, *9*(5), 343–344. <https://doi.org/10.1038/ngeo2702>
- Ngailo, J. A., Mwakasendo, J. A., Kisandu, D. B., & Tippe, D. E. (2016). Rice farming in the Southern Highlands of Tanzania: management practices, socio-economic roles and production constraints. *European Journal of Research in Social Sciences*, *4*(3). [www.idpublications.org](http://www.idpublications.org)
- Ngatia, L., Johnny, M. G. I., Daniel, M., & Robert, T. (2019). Nitrogen and Phosphorus Eutrophication in Marine Ecosystem. *Monitoring of Marine Pollution*, *1*, 1–17. <https://doi.org/http://dx.doi.org/10.5772/57353>
- Ngatia, L., & Taylor, R. (2018). Phosphorus eutrophication and mitigation strategies. In *Phosphorus - Recovery and Recycling* (Issue November 2018). <https://doi.org/10.5772/intechopen.79173>
- Ngoc, B., Ngoc, V., Thanh, M., Thi, T., & Loan, H. (2021). Analysis of the soil to food crops transfer factor and risk assessment of multi-elements at the suburban area of Ho Chi Minh city, Vietnam using instrumental neutron activation analysis (INAA). *Journal of Environmental Management*, *291*(April), 112637. <https://doi.org/10.1016/j.jenvman.2021.112637>

- Nishigaki, T., Sugihara, S., Kobayashi, K., Hashimoto, Y., Kilasara, M., Tanaka, H., Watanabe, T., & Funakawa, S. (2018). Fractionation of phosphorus in soils with different geological and soil physicochemical properties in southern Tanzania. *Soil Science and Plant Nutrition*, *64*(3), 291–299. <https://doi.org/10.1080/00380768.2018.1436406>
- Nkinda, M. S., Rwiza, M. J., Ijumba, J. N., & Njau, K. N. (2020). Quantitative assessment of metal contamination and associated pollution risk in sediments from the Mara River in Tanzania. *Environmental Monitoring and Assessment*, *192*(11). <https://doi.org/10.1007/s10661-020-08681-9>
- Nonga, H. E., Mdegela, R. H., Lie, E., Sandvik, M., & Skaare, J. U. J. (2011). Assessment of farming practices and uses of agrochemicals in Lake Manyara basin, Tanzania. *African Journal of Agricultural Research*, *6*(10), 2216–2230. <https://doi.org/10.5897/AJAR1.27>
- Noroozlo, Y. A., Souiri, M. K., & Delshad, M. (2019). Stimulation Effects of Foliar Applied Glycine and Glutamine Amino Acids on Lettuce Growth. *Open Agriculture*, *4*(1), 164–172. <https://doi.org/10.1515/opag-2019-0016>
- Nriagu, J. O. (1992). Toxic metal pollution in Africa. *Science of the Total Environment*, *121*(C), 1–37. [https://doi.org/10.1016/0048-9697\(92\)90304-B](https://doi.org/10.1016/0048-9697(92)90304-B)
- Nyenje, P. M., Foppen, J. W., Uhlenbrook, S., Kulabako, R., & Muwanga, A. (2010). Eutrophication and nutrient release in urban areas of Sub-Saharan Africa - A review. *Science of the Total Environment*, *408*(3), 447–455. <https://doi.org/10.1016/j.scitotenv.2009.10.020>
- OECD. (2019). *Agri-environmental policy components and policy mechanisms*. <https://doi.org/10.1787/4651e299-en>
- Okoro, E. E., Okolie, A. G., Sanni, S. E., & Omeje, M. (2020). Toxicology of Heavy Metals to Subsurface Lithofacies and Drillers during Drilling of Hydrocarbon Wells. *Scientific Reports*, 1–13. <https://doi.org/10.1038/s41598-020-63107-3>
- Olando, G., Olaka, L. A., Okinda, P. O., & Abuom, P. (2020). Heavy metals in surface sediments of Lake Naivasha, Kenya: Spatial distribution, source identification and ecological risk assessment. *Applied Sciences*, *2*(2), 1–14. <https://doi.org/10.1007/s42452-020-2022-y>

- Ordóñez, A., Loredó, J., De Miguel, E., & Charlesworth, S. (2003). Distribution of heavy metals in the street dusts and soils of an industrial city in Northern Spain. *Archives of Environmental Contamination and Toxicology*, *44*(2), 160–170. <https://doi.org/10.1007/s00244-002-2005-6>
- Paithankar, J. G., Saini, S., Dwivedi, S., Sharma, A., & Chowdhuri, D. K. (2021). Heavy metal associated health hazards: An interplay of oxidative stress and signal transduction. *Chemosphere*, *262*, 128350. <https://doi.org/10.1016/j.chemosphere.2020.128350>
- Panagos, P., Muntwyler, A., Liakos, L., Borrelli, P., Biavetti, I., Bogonos, M., & Lugato, E. (2022). Phosphorus plant removal from European agricultural land. *Journal Fur Verbraucherschutz Und Lebensmittelsicherheit*, *0123456789*. <https://doi.org/10.1007/s00003-022-01363-3>
- Philbert, A., Lyantagaye, S. L., & Nkwengulila, G. (2019). Farmers' pesticide usage practices in the malaria endemic region of North-Western Tanzania: Implications to the control of malaria vectors. *BMC Public Health*, *19*(1), 1–11. <https://doi.org/10.1186/s12889-019-7767-0>
- Phuong, N. M., Kang, Y., Sakurai, K., Iwasaki, K., Kien, C. N., Noi, N. Van, & Son, L. T. (2008). Arsenic contents and physicochemical properties of agricultural soils from the Red River Delta, Vietnam. *Soil Science and Plant Nutrition*, *54*(6), 846–855. <https://doi.org/10.1111/j.1747-0765.2008.00312.x>
- Phuong, N. M., Kang, Y., Sakurai, K., Iwasaki, K., Kien, C. N., Van Noi, N., & Son, L. T. (2010). Levels and chemical forms of heavy metals in soils from red river delta, Vietnam. *Water, Air, and Soil Pollution*, *207*(1–4), 319–332. <https://doi.org/10.1007/s11270-009-0139-0>
- Pierzynski, G. M. (2000). *Methods of phosphorus analysis for soils, sediments, residuals, and waters*. North Carolina State University Raleigh.
- Qiao, D., Wang, G., Li, X., Wang, S., & Zhao, Y. (2020). Pollution, sources and environmental risk assessment of heavy metals in the surface AMD water, sediments and surface soils around unexploited Rona Cu deposit, Tibet, China. *Chemosphere*, *248*, 125988. <https://doi.org/10.1016/j.chemosphere.2020.125988>

- Qin, G., Niu, Z., Yu, J., Li, Z., Ma, J., & Xiang, P. (2021). Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. *Chemosphere*, 267, 129205. <https://doi.org/10.1016/j.chemosphere.2020.129205>
- Ramos-Miras, J. J., Roca-Perez, L., Guzmán-Palomino, M., Boluda, R., & Gil, C. (2011). Background levels and baseline values of available heavy metals in Mediterranean greenhouse soils (Spain). *Journal of Geochemical Exploration*, 110(2), 186–192. <https://doi.org/10.1016/j.gexplo.2011.05.009>
- Ranker, R. E. (1925). Determination of Total Nitrogen in Plants and Plant Solutions: a comparison of Method with Modification. *Journal of Chemical Information and Modeling*, 53(9), 1689–1699.
- Ranker, R. E. (1926). Determination of Total Nitrogen, Nitrate-Nitrogen, and Total Nitrogen not Including Nitrate-Nitrogen: Further Observations on a Modification of the Official Salicylic-Thiosulphate Method Author (s): Emery R. Ranker Source: Annals of the Missouri Bo. *Journal of Chemical Information and Modeling*, 13(4), 391–424.
- Renneson, M., Barbieux, S., & Colinet, G. (2016). Indicators of phosphorus status in soils: significance and relevance for crop soils in Southern Belgium. A review. *Biotechnologie Agronomie Societe Et Environnement*, 20(1), 257–272.
- Renu, K., Chakraborty, R., Myakala, H., Koti, R., Famurewa, A. C., Madhyastha, H., Vellingiri, B., George, A., & Valsala Gopalakrishnan, A. (2021). Molecular mechanism of heavy metals (Lead, Chromium, Arsenic, Mercury, Nickel and Cadmium) - induced hepatotoxicity – A review. *Chemosphere*, 271, 129735. <https://doi.org/10.1016/j.chemosphere.2021.129735>
- Sakané, N., Alvarez, M., Becker, M., Böhme, B., Handa, C., Kamiri, H. W., Langensiepen, M., Menz, G., Misana, S., Mogha, N. G., Mösel, B. M., J. Mwita, E., Oyieke, H., & Van Wijk, M. T. (2011). Classification, characterisation, and use of small wetlands in East Africa. *Wetlands*, 31(6), 1103–1116. <https://doi.org/10.1007/s13157-011-0221-4>
- Sall, M. L., Karim, A., Diaw, D., Gningue-sall, D., Aaron, S. E., & Aaron, J. (2020). Toxic heavy metals: impact on the environment and human health, and treatment with conducting organic polymers, a review. *Environmental Science and Pollution Research*.

- Sánchez-Carrillo, S., Angeler, D. G., Álvarez-Cobelas, M., & Sánchez-Andrés, R. (2011). Freshwater Wetland Eutrophication. *Eutrophication: Causes, Consequences and Control*, 1–394. <https://doi.org/10.1007/978-90-481-9625-8>
- Sangeetha, N., & Ambujam, K. (2021). The overshadow of the human evolvement process in the dynamics of soil drift of an agricultural watershed in Nilgiri Hills, India. *Soil and Water Research*, 2021(2), 103–111. <https://doi.org/10.17221/105/2020-swr>
- Sato, S. (2003). *Phosphorus sorption and desorption in a Brazilian ultisol effects of pH and organic anions on phosphorus bioavailability* /. <http://purl.fcla.edu/fcla/etd/UFE0001359>
- Sayo, S., Kiratu, J. M., & Nyamato, G. S. (2020). Heavy metal concentrations in soil and vegetables irrigated with sewage effluent: A case study of Embu sewage treatment plant, Kenya. *Scientific African*, 8, e00337. <https://doi.org/10.1016/j.sciaf.2020.e00337>
- Schindler, D. W. (2006). Recent advances in the understanding and management of eutrophication. *Limnology and Oceanography*, 51(1part2), 356–363. [https://doi.org/10.4319/lo.2006.51.1\\_part\\_2.0356](https://doi.org/10.4319/lo.2006.51.1_part_2.0356)
- Schoumans, O. F. (2015). Phosphorus leaching from soils: process description, risk assessment and mitigation. *HortScience*, 19(2), 216–217.
- Schoumans, O. F., & Chardon, W. J. (2014). Phosphate saturation degree and accumulation of phosphate in various soil types in The Netherlands. *Geoderma*, 237. <https://doi.org/10.1016/j.geoderma.2014.08.015>
- Schoumans, O. F., Chardon, W. J., Bechmann, M. E., Gascuel-Odoux, C., Hofman, G., Kronvang, B., Rubæk, G. H., Ulén, B., & Dorioz, J. M. (2014). Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. *Science of the Total Environment*, 468–469, 1255–1266. <https://doi.org/10.1016/j.scitotenv.2013.08.061>
- Schullehner, J., Stayner, L., & Hansen, B. (2017). Nitrate, nitrite, and ammonium variability in drinking water distribution systems. *International Journal of Environmental Research and Public Health*, 14(3), 1–9. <https://doi.org/10.3390/ijerph14030276>
- Schwartz, H. F., & Corrales, M. A. P. (1989). *Bean production problems in the tropics*. CIAT.
- Senkondo, Y., Semu, E., & Tack, F. M. G. (2015). Vertical Distribution of Copper in Copper-Contaminated Coffee Fields in Kilimanjaro, Tanzania. *Communications in Soil Science and Plant Analysis*, 46(10), 1187–1199. <https://doi.org/10.1080/00103624.2015.1019085>

- Senkondo, Y. H., Tack, F. M. G., & Semu, E. (2014). Copper Accumulations in Soils, Coffee, Banana, and Bean Plants Following Copper-Based Fungicides in Coffee Farms in Arusha and Kilimanjaro Regions, Tanzania. *Communications in Soil Science and Plant Analysis*, 45(15), 2032–2045. <https://doi.org/10.1080/00103624.2014.919312>
- Senkoro, C., George, L. J., Atanasio, M. E., Charles, W., Mzimhiri, M., Msaky, J., Rose, U., & Lyimo, S. D. (2017). Optimizing fertilizer use within the context of integrated soil fertility management in Zambia. *Fertilizer Use Optimization in Sub-Saharan Africa*, 210–219. <https://doi.org/10.1079/9781786392046.0210>
- Senkoro, C. J., Mtua, K. A., Komba, C., Kazyoba, S. A., Mbogoni, J. D., & Msolla, M. M. (2020). Enhancing the use of appropriate fertilizer for improving rice and maize production in Tanzania. *African Conference on Precision Agriculture*, 160–168.
- Seo, B. H., Kim, H. S., Kwon, S. I., Owens, G., & Kim, K. R. (2019). Heavy metal accumulation and mobility in a soil profile depend on the organic waste type applied. *Journal of Soils and Sediments*, 19(2), 822–829. <https://doi.org/10.1007/s11368-018-2065-5>
- Shah, A., Niaz, A., Ullah, N., Rehman, A., Akhlaq, M., Zakir, M., & Muhammad, S. K. (2013). Comparative study of heavy metals in soil and selected medicinal plants. *Journal of Chemistry*, 17(2), 507–513.
- Sharpley, A. N. (2015). Managing agricultural phosphorus to minimize water quality impacts. *Scientia Agricola*, 73(1), 1–8. <https://doi.org/10.1590/0103-9016-2015-0107>
- Sharpley, A. N., Kleinman, P. J. A., & McDowell, R. W. (2001). Phosphorus loss from land to water: integrating agricultural and environmental management. *Plant and Soil*, 237(2), 287–307. <https://doi.org/10.2307/42951954>
- Sharpley, A. N., & McDowell, R. W. (2016). *Phosphorus loss from land to water: Integrating agricultural and environmental management. Plant and Soil*, 237(2), 287–307.
- Shefali, M., Nayak, S. B., & Gupta, R. K. (2019). Heavy metals in agro-ecosystems and their impacts on human health. *Contaminants in Agriculture and Environment: Health Risks and Remediation*, 58–65. <https://doi.org/10.26832/aesa-2019-cae-0154-05>

- Shemdoe, R. S. (2010). Heavy metal concentrations in soils and leachates of Mtoni dumpsite bordering the Indian Ocean in Dar es salaam, Tanzania. *Scientific Research and Essays*, 5(16), 2143–2147.
- Shreckhise, J., Owen, J. S., Altland, J. E., & White, S. A. (2019). Dolomite and Micronutrient Fertilizer Affect Phosphorus Fate in Pine Bark Substrate used for Containerized Nursery Crop Production. *Soil Science Society of America Journal*, 83(July), 1410–1420. <https://doi.org/10.2136/sssaj2018.12.0493>
- Sillanpää, M. (1982). *Micronutrients and the Nutrient Status of Soils: A Global Study: Food and Agriculture Organization of the United Nation*. Food and Agriculture Organization of the United Nations. [https://books.google.co.tz/books?id=V-\\_KzqroK1EC](https://books.google.co.tz/books?id=V-_KzqroK1EC)
- Simon, F., Mtei, K. M., & Kimanya, M. (2016). Heavy Metals Contamination in Agricultural Soil and Rice in Tanzania: A Review. *International Journal of Environmental Protection and Policy*, 4(1), 16. <https://doi.org/10.11648/j.ijepp.20160401.13>
- Sims, J. T., Maguire, R. O., Leytem, A. B., Gartley, K. L., & Pautler, M. C. (2002). Evaluation of Mehlich 3 as an Agri-Environmental Soil Phosphorus Test for the Mid-Atlantic United States of America. *Soil Science Society of America Journal*, 66(6), 2016–2032. <https://doi.org/10.2136/sssaj2002.2016>
- Singh, P. K., Deshbhratar, P. B., & Ramteke, D. S. (2012). Effects of sewage wastewater irrigation on soil properties, crop yield and environment. *Agricultural Water Management*, 103, 100–104. <https://doi.org/10.1016/j.agwat.2011.10.022>
- Singh, P., Purakayastha, T. J., Mitra, S., Bhowmik, A., & Tsang, D. C. W. (2020). River water irrigation with heavy metal load influences soil biological activities and risk factors. *Journal of Environmental Management*, 270(December 2019), 110517. <https://doi.org/10.1016/j.jenvman.2020.110517>
- Sitoki, L., Gichuki, J., Ezekiel, C., Wanda, F., Mkumbo, O. C., & Marshall, B. E. (2010). The environment of Lake Victoria (East Africa): Current status and historical changes. *International Review of Hydrobiology*, 95(3), 209–223. <https://doi.org/10.1002/iroh.201011226>
- Smith, V. H., & Schindler, D. W. (2009). *Eutrophication science: Where do we go from here?* February. <https://doi.org/10.1016/j.tree.2008.11.009>

- Souri, M. K., Alipanahi, N., Hatamian, M., Ahmadi, M., & Tesfamariam, T. (2018). Elemental profile of heavy metals in garden cress, coriander, lettuce and Spinach, commonly cultivated in Kahrizak, South of Tehran-Iran. *Open Agriculture*, 3(1), 32–37. <https://doi.org/10.1515/opag-2018-0004>
- Srivastava, V., Sarkar, A., Singh, S., Singh, P., de Araujo, A. S. F., & Singh, R. P. (2017). Agroecological responses of heavy metal pollution with special emphasis on soil health and plant performances. *Frontiers in Environmental Science*, 5(OCT), 1–19. <https://doi.org/10.3389/fenvs.2017.00064>
- Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., & Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, 115(33), 8252–8259. <https://doi.org/10.1073/pnas.1810141115>
- Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J., & Vara Prasad, P. V. (2020). Approaches to improve soil fertility in Sub-Saharan Africa. *Journal of Experimental Botany*, 71(2), 632–641. <https://doi.org/10.1093/jxb/erz446>
- Suarez, D. L. (2011). Irrigation water quality assessments. *Agricultural Salinity Assessment and Management: Second Edition, November*, 343–370. <https://doi.org/10.1061/9780784411698.ch11>
- Suresh, G., Ramasamy, V., Meenakshisundaram, V., Venkatachalapathy, R., & Ponnusamy, V. (2011). Influence of mineralogical and heavy metal composition on natural radionuclide concentrations in the river sediments. *Applied Radiation and Isotopes*, 69(10), 1466–1474. <https://doi.org/10.1016/j.apradiso.2011.05.020>
- Tang, Y., Pan, J., Li, B., Zhao, S., & Zhang, L. (2021). Residual and ecological risk assessment of heavy metals in fly ash from co - combustion of excess sludge and coal. *Scientific Reports*, 1–11. <https://doi.org/10.1038/s41598-021-81812-5>
- Teng, Y., Ni, S., Wang, J., Zuo, R., & Yang, J. (2010). A geochemical survey of trace elements in agricultural and non-agricultural topsoil in Dexing area, China. *Journal of Geochemical Exploration*, 104(3), 118–127. <https://doi.org/10.1016/j.gexplo.2010.01.006>

- Torrent, J., Barberis, E., & Gil-Sotres, F. (2007). Agriculture as a source of phosphorus for eutrophication in southern Europe. *Soil Use and Management*, 23(1), 25–35. <https://doi.org/10.1111/j.1475-2743.2007.00122.x>
- Tutic, A., Novakovic, S., Lutovac, M., Biocanin, R., Ketin, S., & Omerovic, N. (2015). The heavy metals in agrosystems and impact on health and quality of life. *Macedonian Journal of Medical Sciences*, 3(2), 345–355. <https://doi.org/10.3889/oamjms.2015.048>
- Uddin, M. M., Peng, G., Wang, Y., Huang, J., & Huang, L. (2021). Pollution status, spatial distribution and ecological risk of heavy metals in sediments of a drinking water lake in South Eastern China. *Environmental Pollutants and Bioavailability*, 33(1), 19–30. <https://doi.org/10.1080/26395940.2021.1894988>
- UoP. (2015). *Hotplate Digestion for Soils / Sediments: ISO900. 5*, 9001.
- Uriyo, A. P., Singh, B. R., & Mtui, A. L. (1977). Phosphate Sorption in Some Tanzanian Soils. *East African Agricultural and Forestry Journal*, 43(2), 124–130. <https://doi.org/10.1080/00128325.1977.11662889>
- URT. (2003). *River Basin Management and Smallholder Smallholder Irrigation Improvement Project*. 8(November).
- URT. (2007). *The environmental management (Soil quality standards) regulation, 2007. United Republic of Tanzania* (Vol. 3, Issue September).
- USEPA. (1992). Human Health Evaluation Manual Supplementary Guidance: Update of Standard Default Exposure Factor. *United States Environmental Protection Agency*, 6. [https://www.epa.gov/sites/production/files/2015-11/documents/oswer\\_directive\\_9200.1-120\\_exposurefactors\\_corrected2.pdf](https://www.epa.gov/sites/production/files/2015-11/documents/oswer_directive_9200.1-120_exposurefactors_corrected2.pdf)
- Usman, A. R. A. (2015). Influence of NaCl-Induced Salinity and Cd Toxicity on Respiration Activity and Cd Availability to Barley Plants in Farmyard Manure-Amended Soil. *Applied and Environmental Soil Science*, 2015. <https://doi.org/10.1155/2015/483836>
- Valev, N. (2012). *Tanzania Fertilizer use - data, chart: The Global Economy*. [https://www.theglobaleconomy.com/Tanzania/fertilizer\\_use/](https://www.theglobaleconomy.com/Tanzania/fertilizer_use/)
- Van Den Bossche, A., De Neve, S., & Hofman, G. (2006). Soil phosphorus status of organic farming in Flanders: an overview and comparison with the conventional management. *Soil Use and Management*, 21(4), 415–421. <https://doi.org/10.1079/sum2005355>

- van der Lee, G. H., Vonk, J. A., Verdonschot, R. C. M., Kraak, M. H. S., Verdonschot, P. F. M., & Huisman, J. (2021). Eutrophication induces shifts in the trophic position of invertebrates in aquatic food webs. *Ecology*, *102*(3), 1–13. <https://doi.org/10.1002/ecy.3275>
- Van Der Zee, S. E. A. T. M., & Van Riemsdijk, W. H. (1986). Sorption kinetics and transport of phosphate in sandy soil. *Geoderma*, *38*(1–4), 293–309. [https://doi.org/10.1016/0016-7061\(86\)90022-4](https://doi.org/10.1016/0016-7061(86)90022-4)
- Van Meirvenne, M., Tariku, M., & Salomez, J. (2007). *Afbakening van de fosfaatverzadigde gebieden in Vlaanderen op basis van een kritische fosfaatverzadigingsgraad van 35%*. 26.
- Vanden Nest, T. (2015). *Long term use of different organic fertilizer types and impact on phosphorus leaching* (Issue January 2015). Doctoral Thesis KU Leuven University.
- Vanlauwe, B., Descheemaeker, K., & Giller, K. (2014). Integrated soil fertility management in Sub-Saharan Africa: Unravelling local adaptation. *Soil*, *1*(2014), 1239–1286. <https://doi.org/10.5194/soild-1-1239-2014>
- Vanni, M. J., Arend, K. K., Bremigan, M. T., Bunnell, D. B., Garvey, J. E., González, M. J., Renwick, W. H., Soranno, P. A., & Stein, R. A. (2005). Linking landscapes and food webs: Effects of omnivorous fish and watersheds on reservoir ecosystems. *BioScience*, *55*(2), 155–167. [https://doi.org/10.1641/0006-3568\(2005\)055\[0155:LLAFWE\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055[0155:LLAFWE]2.0.CO;2)
- Vemic, M., Rousseau, D., Du Laing, G., & Piet, L. (2014). Distribution and fate of metals in the Montenegrin part of Lake Skadar. *International Journal of Sediment Research*, *29*(3), 357–367.
- Verdoodt, A. (2008). Soil Degradation Assessment Guide. *Soil Science*, *151*(2), 184–185. <https://doi.org/10.1097/00010694-199102000-00011>
- Victor, M., & Francis, T. (2013). Productivity of Water in Large Rice (Paddy) Irrigation Schemes in the Upper Catchment of the Great Ruaha River Basin, Tanzania. In *Water Resources Planning, Development and Management: i(tourism)*, 13. <https://doi.org/10.5772/52471>
- Visconti, D., Fiorentino, N., Caporale, A. G., Stinca, A., Adamo, P., Motti, R., & Fagnano, M. (2019). Analysis of native vegetation for detailed characterization of a soil contaminated by tannery waste. *Environmental Pollution*, *252*, 1599–1608. <https://doi.org/10.1016/j.envpol.2019.06.125>

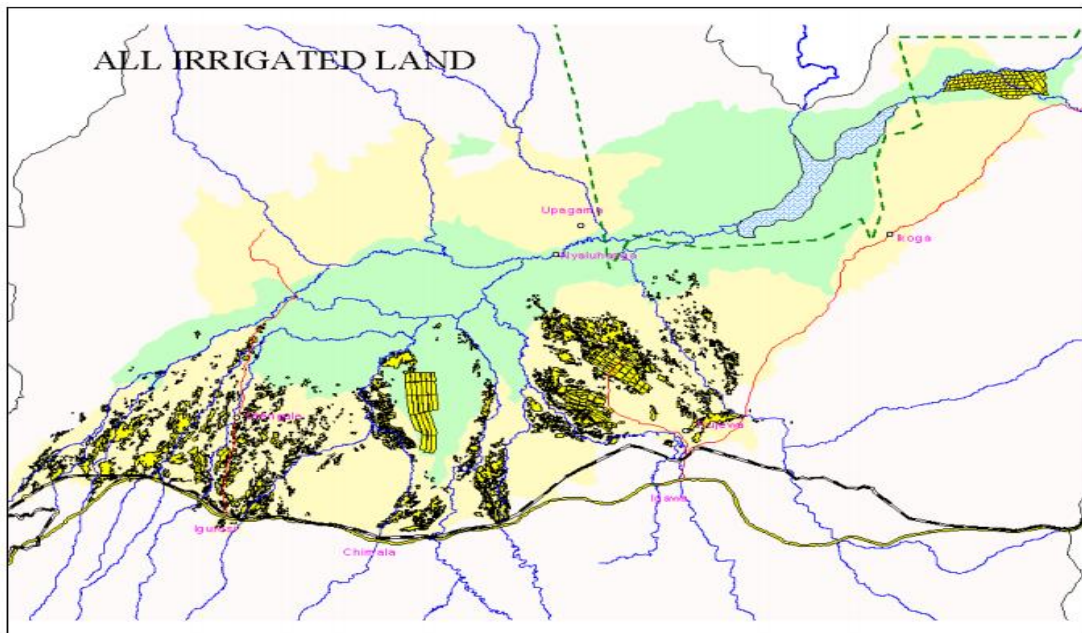
- Visconti, F., & Paz, J. M. de. (2013). Electrical Conductivity Measurements in Agriculture: The Assessment of Soil Salinity. *Intech*, 32(July), 137–144. <https://doi.org/http://dx.doi.org/10.5772/62741>
- Wang, B., Xie, Z., Chen, J., Jiang, J., & Su, Q. (2008). Effects of field application of phosphate fertilizers on the availability and uptake of lead, zinc and cadmium by cabbage (*Brassica chinensis* L.) in a mining tailing contaminated soil. *Journal of Environmental Sciences*, 20(9), 1109–1117. [https://doi.org/10.1016/S1001-0742\(08\)62157-9](https://doi.org/10.1016/S1001-0742(08)62157-9)
- Wang, Q., Wang, C., Yu, W. W., Turak, A., Chen, D., Huang, Y., Ao, J., Jiang, Y., & Huang, Z. (2018). Effects of nitrogen and phosphorus inputs on soil bacterial abundance, diversity, and community composition in chinese fir plantations. *Frontiers in Microbiology*, 9(JUL), 1–10. <https://doi.org/10.3389/fmicb.2018.01543>
- Wang, Y. T., Zhang, T. Q., O'Halloran, I. P., Tan, C. S., & Hu, Q. C. (2016). A phosphorus sorption index and its use to estimate leaching of dissolved phosphorus from agricultural soils in Ontario. *Geoderma*, 274(January), 79–87. <https://doi.org/10.1016/j.geoderma.2016.04.002>
- Wasonga, C., Sigunga, D., & Musandu, A. (2010). Phosphorus requirements by maize varieties in different soil types of Western Kenya. *African Crop Science Journal*, 16(2). <https://doi.org/10.4314/acsj.v16i2.54361>
- Wei, B., & Yang, L. (2010). A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. *Microchemical Journal*, 94(2), 99–107. <https://doi.org/10.1016/j.microc.2009.09.014>
- Weissman, G., Bel, G., Ben-Gal, A., Yermiyahu, U., Alexandrov, B., Rasmussen, K. Ø., & Dahan, O. (2020). Increased irrigation water salinity enhances nitrate transport to deep unsaturated soil. *Vadose Zone Journal*, 19(1), 1–16. <https://doi.org/10.1002/vzj2.20041>
- WHO. (2006). *World Health Organization (WHO) guidelines for the safe use of wastewater excreta and greywater* (Vol. 1). World Health Organization.
- WHO. (2016). Nitrate and nitrite in Drinking Water; WHO Guidelines for Drinking water Quality. *Oncology*, 37(4), 227–231. <https://doi.org/10.1159/000225441>
- WHO. (2018). *WHO Water Quality Guidelines for Drinking-water Quality Third edition-Recommendations*. 1(5), 307–312. <https://doi.org/10.1248/jhs1956.35.307>

- Wickama, J. M., & Mowo, J. G. (2001). Using local resources to improve soil fertility in Tanzania. *Managing Africa's Soils*, 21, 14. <http://pubs.iied.org/pdfs/9041IIED.pdf>
- Wilson, D. (2013). *Soil pH and Soil Fertility*.
- Wynants, M., Kelly, C., Mtei, K., Munishi, L., Patrick, A., Rabinovich, A., Nasser, M., Gilvear, D., Roberts, N., Boeckx, P., Wilson, G., Blake, W. H., & Ndakidemi, P. (2019). Drivers of increased soil erosion in East Africa's agro-pastoral systems: Changing interactions between the social, economic and natural domains. *Regional Environmental Change*, 19(7), 1909–1921. <https://doi.org/10.1007/s10113-019-01520-9>
- Xu, Y., Wu, Y., Han, J., & Li, P. (2017). The current status of heavy metal in lake sediments from China: Pollution and ecological risk assessment. *Ecology and Evolution*, 7(14), 5454–5466. <https://doi.org/10.1002/ece3.3124>
- Xu, Z., Zhang, X., Xie, J., Yuan, G., Tang, X., Sun, X., & Yu, G. (2014). Total nitrogen concentrations in surface water of typical agro- and forest ecosystems in China, 2004–2009. *PLoS ONE*, 9(3), 2004–2009. <https://doi.org/10.1371/journal.pone.0092850>
- Yang, X., Wu, X., Hao, H., & He, Z. (2008). Mechanisms and assessment of water eutrophication. *Journal of Zhejiang University SCIENCE B*, 9(3), 197–209. <https://doi.org/10.1631/jzus.B0710626>
- Yuvaraj, A., Govarthanan, M., Karmegam, N., Biruntha, M., Kumar, D. S., Arthanari, M., Govindarajan, R. K., Tripathi, S., Ghosh, S., Kumar, P., Kannan, S., & Thangaraj, R. (2021). Metallothionein dependent-detoxification of heavy metals in the agricultural field soil of industrial area: Earthworm as field experimental model system. *Chemosphere*, 267. <https://doi.org/10.1016/j.chemosphere.2020.129240>
- Zhang, Y., Finn, D., Bhattacharyya, R., Dennis, P. G., Doolette, A. L., Smernik, R. J., Dalal, R. C., Meyer, G., Lombi, E., Klysubun, W., Jones, A. R., Wang, P., Menzies, N. W., & Kopittke, P. M. (2021). Long-term changes in land use influence phosphorus concentrations, speciation, and cycling within subtropical soils. *Geoderma*, 393(September 2020), 115010. <https://doi.org/10.1016/j.geoderma.2021.115010>
- Zhao, K., Liu, X., Xu, J., & Selim, H. M. (2010). Heavy metal contaminations in a soil-rice system: Identification of spatial dependence in relation to soil properties of paddy fields. *Journal of Hazardous Materials*, 181(1–3), 778–787. <https://doi.org/10.1016/j.jhazmat.2010.05.081>

- Zhao, X., Joo, J. C., & Kim, J. Y. (2021). Evaluation of heavy metal phytotoxicity to *Helianthus annuus* L. using seedling vigor index-soil model. *Chemosphere*, 275, 130026. <https://doi.org/10.1016/j.chemosphere.2021.130026>
- Zhou, L., Yang, B., Xue, N., Li, F., Seip, H. M., Cong, X., Yan, Y., Liu, B., Han, B., & Li, H. (2014). Ecological risks and potential sources of heavy metals in agricultural soils from Huanghuai Plain, China. *Environmental Science and Pollution Research*, 21(2), 1360–1369. <https://doi.org/10.1007/s11356-013-2023-0>
- Zhou, T., Zhao, M., Zhao, X., Guo, Y., & Zhao, Y. (2021). Simultaneous remediation and fertility improvement of heavy metals contaminated soil by a novel composite hydrogel synthesized from food waste. *Chemosphere*, 275, 129984. <https://doi.org/10.1016/j.chemosphere.2021.129984>

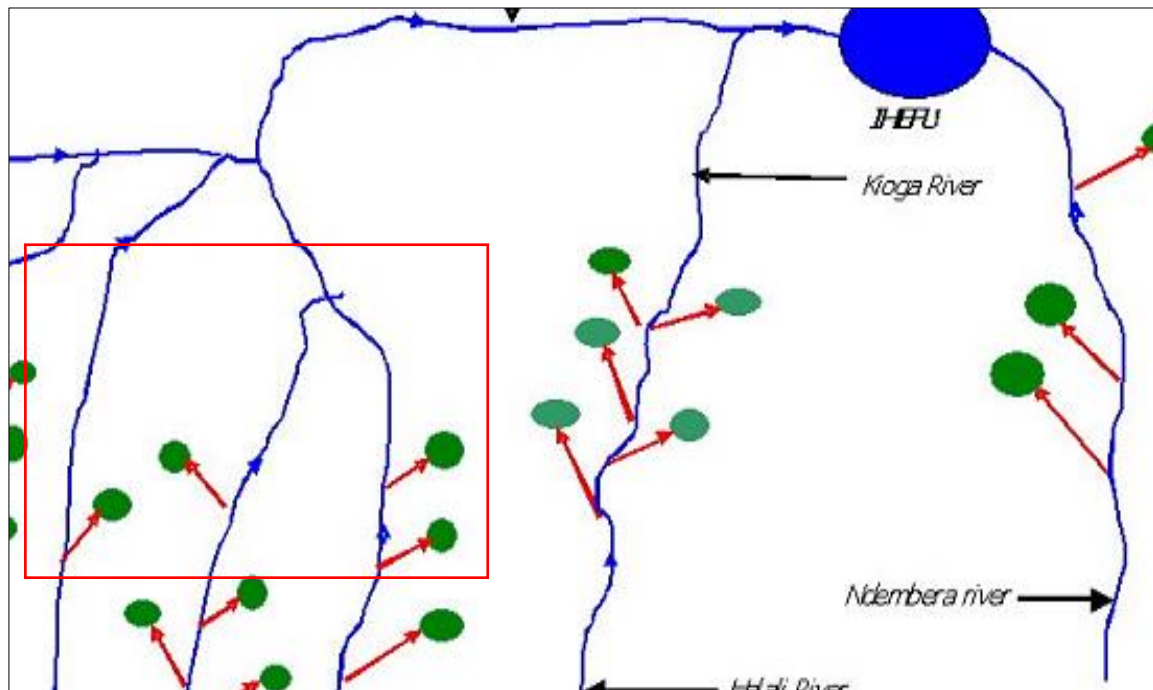
## APPENDICES

**Appendix 1: Map of Usangu showing irrigated lands (yellow), seasonal wetland (green) and permanent wetlands (Blue)**

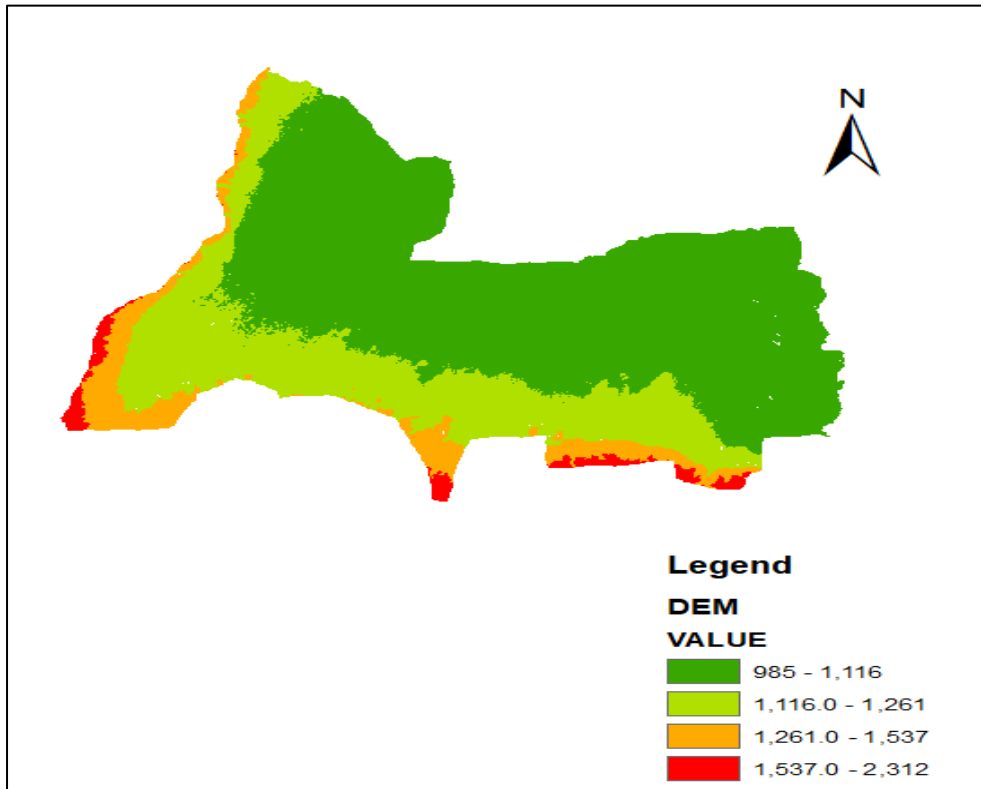


Source: (Fox, 2004)

**Appendix 2: Rivers and irrigation study area in (red box) in Usangu**



### Appendix 3: Digital Elevation Model in the study area Usangu agro-ecosystem



Source: (Author)

**Appendix 4; Limit for Detection (LODs in mg/kg) for instrument and method for selected potentially toxic elements in Certified Reference Materials (CRM). Experimental (mg/kg) and reference (mg/kg) values of CRM (SCP EnviroMAT-S150123029 using Mehlich 3 method (M3) and SS-2 EnvironMAT-S150827031 using aqua regia (AQ)) are provided**

Element	Instrumental LOD	M3			AQ		
		Method LOD	SCP-Experimental Values	SCP-Reference Values	Method LOD (mg/kg)	Experimental Values-SS2	Reference Values-SS2
Cu	0.50	0.51	0.38	0.41	0.30	110.6	120
Pb	2.50	2.50	0.10	0.10	0.28	222.2	244
Zn	0.25	0.25	1.05	1.09	1.68	220.1	281
Ag	0.00	0.01	-	-	0.05	3.4	3.9
As	0.002	0.01	0.28	0.26	0.03	3.2	3.36
Cd	0.002	0.01	0.05	0.05	0.03	0.78	0.9
Co	0.001	0.02	0.23	0.25	0.03	5.16	6.9
Cr	0.004	0.03	0.30	0.33	0.03	79.7	92.6
Hg	0.02	0.001	-	-	0.01	0.048	0.059
Mo	0.01	0.03	0.53	0.57	0.10	1.01	1.03
Ni	0.003	0.06	0.50	0.51	0.13	19.1	25.1

**Appendix 5: The calculated ratio of PTEs versus Tanzania and USEPA maximum acceptable limit as estimates of PTEs contamination hierarchy among land-use groups in Usangu agro-ecosystem**

Land Use	Group	AQ-Cr/TZ	AQ-Co/TZ	AQ-Fe/TZ	AQ-Mn/TZ	AQ-Zn/TZ	AQ-Ag/TZ	AQ-As/TZ
Conservation Area	I	0.19	3.41	1636.60	0.15	0.13	38.58	1.71
	II	0.16	4.13	1644.67	0.35	0.14	69.99	1.67
Maize farming	I	-	-	-	-	-	-	-
	II	0.14	2.99	1461.81	0.26	0.13	18.81	1.46
Paddy farming	I	0.16	3.07	1470.16	0.11	0.12	37.18	1.26
	II	0.13	2.39	1444.62	0.20	0.13	36.82	1.66

Land Use	Group	AQ-Cd/TZ	AQ-Cu/TZ	AQ-Hg/TZ	AQ-Mo/TZ	AQ-Ni/TZ	AQ-Pb/TZ	AQ-Se/TZ
Conservation Area	I	0.01	0.02	0.001	306.90	0.06	0.03	0.09
	II	0.03	0.01	0.001	522.66	0.02	0.04	0.20
Maize farming	I	-	-	-	-	-	-	-
	II	0.04	0.01	0.001	471.96	0.02	0.04	0.18
Paddy farming	I	0.02	0.02	0.002	223.77	0.05	0.03	0.11
	II	0.03	0.01	0.002	354.08	0.02	0.03	0.20

Land Use	Group	AQ-Cr/USEPA	AQ-Co/USEPA	AQ-Fe/USEPA	AQ-Mn/USEPA	AQ-Zn/USEPA	AQ-Ag/USEPA	AQ-As/USEPA
Conservation Area	I	18.46	3.41	1636.60	53.88	3.82	38.58	8.56
	II	15.61	4.13	1644.67	126.32	4.28	69.99	8.36
Maize farming	I	-	-	-	-	-	-	-
	II	13.95	2.99	1461.81	91.70	3.91	18.81	7.28
Paddy farming	I	16.43	3.07	1470.16	38.19	3.46	37.18	6.31
	II	12.58	2.39	1444.62	73.10	3.98	36.82	7.85

Land Use	Group	AQ-Cd/USEPA	AQ-Cu/USEPA	AQ-Hg/USEPA	AQ-Mo/USEPA	AQ-Ni/USEPA	AQ-Pb/USEPA	AQ-Se/USEPA
Conservation Area	I	0.14	2.29	0.56	306.90	0.11	55.41	0.09
	II	0.34	0.92	0.56	522.66	0.04	80.37	0.20
Maize farming	I	-	-	-	-	-	-	-
	II	0.36	0.77	0.57	471.96	0.03	71.29	0.18
Paddy farming	I	0.18	2.03	0.63	223.77	0.10	52.45	0.11
	II	0.28	0.92	0.73	354.08	0.04	63.92	0.20

**Appendix 6: The calculated ratio of PTEs versus Tanzania and USEPA maximum acceptable limit as an estimates of PTEs contamination hierarchy among irrigation schemes in Usangu agro-ecosystem**

Scheme	Group	AQ-Cr/TZ	AQ-Co/TZ	AQ-Mn/TZ	AQ-Zn/TZ	AQ-Ag/TZ	AQ-As/TZ	AQ-Cd/TZ	AQ-Cu/TZ	AQ-Hg/TZ	AQ-Mo/TZ	AQ-Ni/TZ	AQ-Pb/TZ
Chimala	I	0.21	4.11	0.13	0.14	52.22	1.61	0.02	0.03	0.002	262.14	0.07	0.03
Igalako	I	0.13	2.98	0.19	0.12	22.43	1.33	0.04	0.01	0.001	332.66	0.02	0.03
Ihahi	I	0.11	1.83	0.21	0.13	31.30	1.54	0.03	0.01	0.002	417.30	0.02	0.03
Ilaji	I	0.17	2.76	0.18	0.12	65.43	1.79	0.02	0.01	0.001	331.28	0.03	0.03
Isenyela	I	0.06	1.03	0.18	0.05	15.95	1.06	0.02	0.00	0.001	392.26	0.0040	0.02
Kapunga	I	0.15	2.59	0.10	0.12	42.39	1.28	0.02	0.02	0.002	260.85	0.04	0.03
Mabadaga	II	0.34	6.43	0.13	0.14	9.86	0.87	0.04	0.04	0.002	47.18	0.15	0.02
Mahongole	II	0.15	3.29	0.28	0.14	42.08	1.70	0.03	0.01	0.002	417.34	0.02	0.04
Mubuyuni	II	0.18	3.66	0.10	0.11	30.86	1.26	0.02	0.03	0.002	162.26	0.07	0.03
Uturo	II	0.20	3.87	0.13	0.11	28.91	1.45	0.01	0.03	0.002	233.34	0.06	0.02

Scheme	Group	AQ-Cr/USEPA	AQ-Co/USEPA	AQ-Mn/USEPA	AQ-Zn/USEPA	AQ-Ag/USEPA	AQ-As/USEPA	AQ-Cd/USEPA	AQ-Cu/USEPA	AQ-Hg/USEPA	AQ-Mo/USEPA	AQ-Ni/USEPA	AQ-Pb/USEPA
Chimala	I	20.59	4.11	47.74	4.13	52.22	8.03	0.17	2.83	0.95	262.14	0.14	58.41
Igalako	I	12.79	2.98	69.69	3.55	22.43	6.64	0.35	0.86	0.57	332.66	0.04	68.41
Ihahi	I	11.30	1.83	75.22	3.97	31.30	7.68	0.26	0.80	0.73	417.30	0.03	59.60
Ilaji	I	16.91	2.76	66.26	3.58	65.43	8.95	0.23	1.39	0.22	331.28	0.06	60.95
Isenyela	I	5.80	1.03	63.44	1.43	15.95	5.31	0.18	0.20	0.45	392.26	0.01	41.28
Kapunga	I	14.74	2.59	35.80	3.73	42.39	6.40	0.19	1.74	0.62	260.85	0.09	54.69
Mabadaga	II	34.24	6.43	47.38	4.19	9.86	4.35	0.36	3.92	0.99	47.18	0.30	38.89
Mahongole	II	14.72	3.29	99.67	4.26	42.08	8.51	0.34	0.73	0.66	417.34	0.03	76.34
Mubuyuni	II	18.25	3.66	37.00	3.22	30.86	6.30	0.17	2.50	0.70	162.26	0.13	51.52
Uturo	II	19.55	3.87	46.02	3.37	28.91	7.26	0.14	2.61	0.60	233.34	0.12	48.70

**Appendix 7: The spatial bioavailable PTEs (M3) distribution in different irrigation schemes in Usangu agro-ecosystem**

<b>Scheme</b>	<b>Group</b>	<b>Al (mg/kg)</b>	<b>Cu (mg/kg)</b>	<b>Fe (mg/kg)</b>	<b>Mn (mg/kg)</b>	<b>Pb (mg/kg)</b>	<b>Zn (mg/kg)</b>	<b>Ag (µg/kg)</b>	<b>As (µg/kg)</b>
Ilaji	I	277.06	1.53	248.68	141.61	1.51	2.43	9.98	134.57
Isenyela	I	210.72	0.31	107.89	147.85	1.31	1.46	0.20	468.24
Kapunga	I	346.16	1.83	190.58	104.52	1.89	1.81	4.49	258.36
Mabadaga	I	201.95	2.11	155.81	64.51	0.64	0.46	8.37	140.15
Mubuyuni	I	285.44	3.44	288.81	98.92	1.67	2.02	33.12	86.85
Uturo	I	199.15	4.14	245.48	171.84	2.74	2.95	7.20	114.72
Chimala	II	182.20	2.29	324.08	119.00	0.53	2.47	0.00	32.75
Igalako	II	303.15	0.70	160.35	164.50	1.68	2.55	9.65	166.13
Ihahi	II	188.54	0.81	158.31	226.91	1.90	3.38	8.70	245.45
Mahongole	II	287.42	0.68	154.62	201.27	1.69	3.16	16.59	320.52
<b>Scheme</b>	<b>Group</b>	<b>Cd (µg/kg)</b>	<b>Co (µg/kg)</b>	<b>Cr (µg/kg)</b>	<b>Hg (µg/kg)</b>	<b>Mo (µg/kg)</b>	<b>Ni (µg/kg)</b>	<b>Sb (µg/kg)</b>	<b>Se (µg/kg)</b>
Ilaji	I	23.94	291.19	46.08	0.00	0.00	134.54	0.00	1161.09
Isenyela	I	27.19	325.74	6.09	0.00	16.44	93.28	0.00	2395.93
Kapunga	I	19.01	631.04	39.60	0.17	0.72	307.89	0.50	1912.27
Mabadaga	I	12.37	912.72	99.03	0.00	1.35	1770.17	0.20	836.92
Mubuyuni	I	19.45	987.06	84.92	0.00	0.18	1278.17	1.49	613.27
Uturo	I	17.52	1619.78	55.81	0.00	3.45	799.26	1.79	934.04
Chimala	II	18.25	699.57	101.46	0.00	0.00	1086.71	0.93	142.44
Igalako	II	36.78	526.17	21.28	0.35	3.81	217.74	0.17	1478.35
Ihahi	II	36.95	489.31	13.46	0.00	11.80	110.46	0.63	2204.81
Mahongole	II	39.32	455.84	13.49	0.10	5.67	74.14	0.43	2470.70

**Appendix 8: The ratio of PTEs in M3 and AQ to estimate its percentage availability for plant uptake in agricultural soils of UA**

Scheme	Group	M3-Al/AQ-Al	M3-Co/AQ-Co	M3-Cr/AQ-Cr	M3-Fe/AQ-Fe	M3-K/AQ-K	M3-Mg/AQ-Mg	M3-Mn/AQ-Mn	M3-S/AQ-S	M3-Zn/AQ-Zn
Ilaji	I	0.03	0.19	0.003	0.03	0.36	0.48	0.39	0.16	0.14
Isenyela	I	0.07	0.40	0.001	0.03	0.32	0.44	0.49	0.63	0.22
Kapunga	I	0.04	0.24	0.003	0.03	0.26	0.46	0.58	0.36	0.10
Mabadaga	I	0.02	0.12	0.003	0.02	1.24	0.51	0.28	0.31	0.02
Mubuyuni	I	0.06	0.27	0.005	0.04	0.33	0.24	0.58	0.24	0.13
Uturo	I	0.03	0.46	0.003	0.03	0.40	0.40	0.81	0.27	0.17
Chimala	II	0.03	0.17	0.005	0.04	0.20	0.21	0.50	0.28	0.12
Igalako	II	0.04	0.31	0.002	0.03	0.47	0.58	0.56	0.51	0.14
Ihahi	II	0.03	0.34	0.001	0.03	0.35	0.57	0.67	0.33	0.18
Mahongole	II	0.03	0.25	0.001	0.02	0.47	0.74	0.42	0.32	0.15

Scheme	Group	M3-Ag/AQ-Ag	M3-As/AQ-As	M3-Cd/AQ-Cd	M3-Cu/AQ-Cu	M3-Hg/AQ-Hg	M3-Mo/AQ-Mo	M3-Ni/AQ-Ni	M3-Pb/AQ-Pb	M3-Se/AQ-Se
Ilaji	I	0.17	0.09	1.09	0.45	0.00	0.00	0.05	0.26	0.47
Isenyela	I	0.02	0.45	1.73	0.84	0.00	0.04	0.25	0.32	1.18
Kapunga	I	0.41	0.20	1.14	0.53	0.11	0.01	0.08	0.35	0.79
Mabadaga	I	0.93	0.16	0.46	0.28	0.00	0.03	0.12	0.18	0.43
Mubuyuni	I	10.38	0.08	1.29	0.69	0.00	0.00	0.19	0.37	0.42
Uturo	I	0.52	0.08	1.42	0.96	0.00	0.02	0.16	0.59	0.61
Chimala	II	0.00	0.02	1.13	0.41	0.00	0.00	0.16	0.09	0.07
Igalako	II	0.48	0.13	1.30	0.47	0.07	0.01	0.15	0.27	0.51
Ihahi	II	1.17	0.17	1.55	0.54	0.00	0.04	0.08	0.35	0.50
Mahongole	II	0.68	0.18	1.16	0.49	0.02	0.01	0.05	0.23	0.58

**Appendix 9: Correlation coefficient of PTEs concentrations in agricultural soils from Usangu agro-ecosystem**

PTEs	Al (mg/Kg)	Cu (mg/kg)	Fe (mg/Kg)	Mn (mg/kg)	Pb (mg/kg)	Zn (mg/Kg)					
Al (mg/kg)	1										
Cu (mg/kg)	-0.068	1									
Fe (mg/kg)	0.111	0.592***	1								
Mn (mg/kg)	-0.151*	-0.309***	-0.203**	1							
Pb (mg/kg)	-0.193**	0.345***	-0.148*	0.155*	1						
Zn (mg/kg)	-0.226**	-0.066	-0.035	0.362**	0.189**	1					
PTEs	Ag (µg/kg)	As (µg/kg)	Cd (µg/kg)	Co (µg/kg)	Cu (µg/kg)	Hg (µg/kg)	Mo (µg/kg)	Ni (µg/kg)	Pb (µg/kg)	Sb (µg/kg)	Se (µg/kg)
Ag (µg/kg)	1										
As (µg/kg)	0.028	1									
Cd (µg/kg)	-0.05	0.29***	1								
Co (µg/kg)	-0.022	-0.001	-0.198**	1							
Cu (µg/kg)	-0.04	-0.113	-0.366***	0.884***	1						
Hg (µg/kg)	-0.214**	-0.095	0.086	0.116	0.14*	1					
Mo (µg/kg)	-0.074	0.584***	0.389***	-0.319***	-0.394***	0.039	1				
Ni (µg/kg)	-0.03	-0.185**	-0.304***	0.916***	0.94***	0.157*	-0.44***	1			
Pb (µg/kg)	0.062	0.611***	0.556***	-0.151*	-0.27***	-0.175*	0.47***	-0.31***	1		
Sb (µg/kg)	-0.051	0.278***	-0.075	0.252***	0.285***	-0.095	0.31***	0.199***	0.136	1	
Se (µg/kg)	-0.01	0.504***	0.573***	-0.524***	-0.66***	0.071	0.56***	-0.63***	0.566***	-0.25***	1
Zn (mg/kg)	0.047	0.553***	0.457***	0.098	0.039	0.07	0.372***	0.008	0.573***	-0.023	0.506***

The correlation with asterisk (\*) are statistically significant at \*  $P < 0.05$ , \*\*  $P < 0.01$ , \*\*\*  $P < 0.001$ .

**Appendix 10: Concentration of total (aqua regia extracts) and bioavailable (Mehlich 3 extracts) PTEs in agricultural soils from Usangu-irrigation schemes**

Group	Total PTEs		Bioavailable PTEs	
	I	II	I	II
Al (mg/kg)	7729.24±3069	8146.79±2636	302.4±160	243.27±142
Cr (µg/kg)	16620±5.18	13070±3.88	55.04±37.05	19±21.55
Fe (mg/kg)	7428.21±1553	7288.99±1560	224.35±88.95	164.84±60.35
Mn (mg/kg)	198.25±89.54	401.32±153.72	112.59±63.06	200.84±80.91
Pb (µg/kg)	5272.27±1650.4	6655.55±1994.69	1870±800	1730±530
Zn (mg/kg)	17.47±3.84	19.86±4.61	1.99±1.05	3.09±1.29
Ag (µg/kg)	37.31±44.68	33.56±38.06	13.04±1.3	10.93±15.26
As (µg/kg)	1303.21±348.40	1544.11±349.54	190.17±144.16	241.8±191.74
Cd (µg/kg)	18.03±8.64	29.99±11.95	19.22±7.01	36.82±8
Co (µg/kg)	3113±117	1900.37±110	829.01±540	496.28±160
Cu (µg/kg)	4109.06±1588.06	1754.04±1084	2510±1440	810±420
Hg (µg/kg)	3.13±1.95	3.42±2.04	0.09±0.99	0.1±0.42
Mo (µg/kg)	231.5±154.2	392.16±181.24	1.23±3.18	7.69±13.08
Ni (µg/kg)	5191.63±2468	1854.23±1301.68	656.75±734.64	165.17±217.61
Sb (µg/kg)	29.92±25.49	23.65±16.94	0.88 ±0.88	0.48±0.42
Se (µg/kg)	2073.4±712.13	3927.53±1089.7	1387.31±956.59	2038.14±1305.11

**Appendix 11: Chemical composition of studied sediments from different sampling points Usangu agro-ecosystem**

Sample ID	pH	%OM	%OC	OC (mg/kg)	N%	Total N (mg/kg)	P (mg/kg)	Cr (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Co (mg/kg)
CH S1	5.1	2.51	1.44	14.43	0.06	0.62	3.27	0.010	0.86	0.12	1.72
IGA S1	6.5	3.18	1.83	18.25	0.12	1.18	3.23	0.052	0.98	0.17	0.92
IGA S2	5.8	2.98	1.71	17.10	0.15	1.46	4.20	0.005	0.72	0.10	1.31
KAP CH2 S2	4.9	5.95	3.42	34.20	0.11	1.06	4.89	0.001	0.61	0.09	0.99
KAP S1	5.3	4.89	2.81	28.12	0.19	1.90	3.75	0.001	0.51	0.13	1.19
KAP S3	5.2	2.12	1.22	12.16	0.19	1.85	4.89	0.001	0.61	0.09	0.99
MAH S1	6.3	5.22	3.00	30.02	0.18	1.79	5.12	ND	0.57	0.08	0.89
MB S1	5.7	4.89	2.81	28.12	0.21	2.07	4.66	0.003	0.64	0.09	1.10
MB S2	7.0	2.38	1.37	13.68	0.09	0.90	3.74	0.007	0.79	0.11	1.51
MB S3	5.8	4.03	2.32	23.18	0.21	2.07	4.78	0.002	0.63	0.09	1.05
MB S5	5.4	1.26	0.72	7.22	0.17	1.68	3.48	ND	1.80	0.04	0.97
MB S6	5.8	2.22	1.27	12.73	0.17	1.74	2.00	ND	0.81	0.05	1.94
UK S1	5.3	6.28	3.61	36.10	0.11	1.12	2.61	ND	0.41	0.18	1.39
UT S1	5.2	1.39	0.80	7.98	0.41	4.09	4.49	0.003	0.67	0.10	1.18

*ND: means the concentration of the respective element was below detection limits*

**Appendix 12: Chemical composition of studied sediments from different irrigation schemes in Usangu agro-ecosystem**

Scheme	pH	%OM	%OC	OC (mg/kg)	N%	Total N (mg/kg)	P (mg/kg)	Cr (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Co (mg/kg)
Chang'ombe	5.1	2.51	1.44	14.43	0.06	0.62	3.27	0.01	0.86	0.12	1.72
Igalako	6.2	3.08	1.77	17.68	0.13	1.32	3.72	0.03	0.85	0.14	1.11
Kapunga	5.2	4.32	2.48	24.83	0.16	1.61	4.51	ND	0.58	0.10	1.06
Mahongole	6.3	5.22	3.00	30.02	0.18	1.79	5.12	ND	0.57	0.08	0.89
Mubuyuni	5.9	2.96	1.70	16.99	0.17	1.69	3.73	0.01	0.93	0.08	1.31
Ukwavile	5.3	6.28	3.61	36.10	0.11	1.12	2.61	ND	0.41	0.18	1.39
Uturo	5.2	1.39	0.80	7.98	0.41	4.09	4.49	ND	0.67	0.10	1.18

*ND: means the concentration of the respective element was below detection limits*

### Appendix 13: Soil particle distribution and textural classes for studied soils from UA

Scheme	Sand (%)	Silt (%)	Clay (%)	Texture class
Chimala	12.40	36.00	51.60	clay
Igalako	28.22	32.55	39.24	clay loam
Kapunga	21.35	32.40	46.25	sandy clay loam
Mahongole	13.40	38.00	48.60	silty clay
Mubuyuni	16.66	39.35	44.00	silty clay loam
Ihahi	18.66	38.35	45.00	silty clay loam
Isenyela	15.66	39.35	47.20	silty clay loam
Ilaji	6.00	29.00	65.00	silty clay/clay
Uturo	42.93	23.07	34.00	silty clay loam

**Appendix 14: Paddy rice production in Usangu, where about 105,000 tons of paddy rice or about 66,000 tons of rice, equivalent to 14.4% of annual paddy rice production in Tanzania are produced from Usangu agro-ecosystem. In the normal dry year, the area under paddy production is approximately 89.79% (22,000 ha out of 24,500 ha) of the entire cultivated land in Usangu**

Activity	Farm size (ha)	Paddy yield (kg/ha)	Scheme
I	0.3	788	Uturo, Igalako, Mahongole, Ilaji, Isenyela, Mabadaga,
II	0.5	1500	Ihahi, Chimala
III	6	1600	Mubuyuni, Kapunga,
IV	1.25	3000	Mubuyuni, Kapunga, Ihahi,

(Kadigi et al., 2003).

NB:-**Activity I** = smallholder farmers, cultivating rainfed paddy, using hand hoe and family labour; **Activity II** = smallholder farmers, cultivating rainfed paddy, using tractors and hired labour; **Activity III** = smallholder farmers, hiring NAFCO (National Agriculture and Food Corporation) farms, cultivating irrigated paddy, using tractors, fertilizer and hired labour; and **Activity IV** = smallholder farmers, cultivating irrigated paddy, using tractors, fertilizer and hired labour; source (Kadigi et al., 2003).

**Appendix 15: Paddy production trend in Mbarali district and area under paddy production from 1992/93 to 2001/2002**

<b>Year</b>	<b>Area (ha)</b>	<b>Yield (t/ha)</b>	<b>%change in area (ha)</b>	<b>%Change in yield (t)</b>
1992/93	24,444	1.9		
1993/94	24,900	2.2	18.0	15.8
1994/95	26,777	1.8	-12.0	-18.2
1995/96	36,000	2.2	61.8	20.4
1996/97	35,000	1.8	-21.5	-19.2
1997/98	23,834	3.3	28.4	88.6
1998/99	20,342	1.5	-61.2	-54.5
1999/00	17,600	2.0	15.4	33.3
2000/01	28,800	2.8	131.9	41.7
2001/02	28,400	3.0	4.4	5.8
<b>Average</b>	<b>26,610</b>	<b>2.2</b>		
<b>St. deviation</b>	<b>5,796</b>	<b>20.03</b>	<b>0.589</b>	

Source: Mbarali district agricultural office (2002)

### Appendix 16: Potential management activities in irrigation schemes studied in Usangu agro-ecosystem

S/N	Irrigation schemes	Management practices	Dominated by	Scheme Group
1	<ol style="list-style-type: none"> <li>1. Mahangole</li> <li>2. Chimala</li> <li>3. Igalako</li> <li>4. Ihahi</li> <li>5. Ilaji</li> </ol>	<ul style="list-style-type: none"> <li>• Small farms per farmers with little fertilizer and manure applications</li> <li>• Located closer to residential areas</li> <li>• Unimproved irrigation infrastructures</li> <li>• Use hand hoe and other simple tools for land preparation</li> <li>• Involves mixed cropping (paddy is rotated with other horticultural crops)</li> <li>• Flooding is common system of irrigation</li> <li>• Bathing and domestic washing are conducted in irrigation channels</li> <li>• Domestic wastes are directly linked to farming areas and irrigation channels</li> <li>• Are late planted due to being late reached by irrigation waters</li> <li>• They are located along TAZAM and TAZARA line</li> <li>• Located in areas with altitude ranging from 1100 to 2100 meter above sea level (m.a.s.l)</li> <li>• Common crops grown in the area include Maize, rice, potatoes, and other horticultural crops</li> <li>• Less mechanized and uses simple to medium farm machines</li> <li>• Mostly farms are owned by farmers themselves through customary land lease</li> </ul>	Smallholder farmers	<p style="text-align: center;"><b>II</b> (Farming and scattered settlements (mixed agricultural schemes))</p>
2	<ol style="list-style-type: none"> <li>1. Isenyela</li> <li>2. Kapunga</li> <li>3. Mabadaga</li> <li>4. Mubuyuni</li> <li>5. Uturo</li> </ol>	<ul style="list-style-type: none"> <li>• Larger and small farms per farmers with high use of mineral fertilizers and manure applications</li> <li>• Located far from residential areas and only dominated by farmlands</li> <li>• Have highly improved irrigation infrastructures and farms are well organized to blocks</li> <li>• Dominated by monoculture farming practices for easy mechanization</li> <li>• Highly mechanized with use of highly advanced farming machines and agrochemicals</li> <li>• Some have crop processing industries onsite</li> <li>• Depend on modernized farming tools such as tractors, combine harvester, power tillers etc, which can have influence of land use quality</li> <li>• Involves monocropping (paddy is grown year after year without rotation with other crops)</li> <li>• Flooding is common system of irrigation</li> <li>• Bathing and washing are conducted in irrigation channels</li> </ul>	Large scale farmers	<p style="text-align: center;"><b>I</b> (Farming areas alone (pure agricultural schemes))</p>

		<ul style="list-style-type: none"> <li>• Domestic wastes are not directly linked to farming areas and irrigation channels</li> <li>• Are early planted due to being reached by irrigation water early</li> <li>• They are located in the lowland of Usangu basin receiving rain surfaces water from upland areas</li> <li>• Located in altitude ranging from 904 to 1600 meters above sea level (m.a.s.l)</li> <li>• Common crops grown in the area is paddy with patches of maize and horticultural crops</li> <li>• Chemical weed control is the dominant weed management option in the area</li> <li>• Have higher use of chemical fertilizer up to 250 kg N/acre</li> <li>• Have higher frequency of chemical pesticides and herbicides application up 8 times per season.</li> <li>• Have higher water ponding in paddy farming up to 25 cm depth to some schemes such as Kapunga</li> <li>• Involves deep tillage with highly homogenization of the plough layer for easy transplanting</li> <li>• Farm acquisition is by renting for specified period varying from 1 year to 5 years which could influence management.</li> </ul>		
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## RESEARCH OUTPUT

### 1. Journal publications (In SCI- Indexed Journals)

- Mng'ong'o, M.,** Munishi, L. K., Ndakidemi, P. A., Blake, W., Comber, S., & Hutchinson, T. H. (2021). Toxic metals in East African agro-ecosystems: Key risks for sustainable food production. *Journal of Environmental Management*, 294(May), 112973. <https://doi.org/10.1016/j.jenvman.2021.112973>
- Mng'ong'o, M.,** Munishi, L. K., Blake, W., Comber, S., Hutchinson, T. H., & Ndakidemi, P. A. (2021). Soil fertility and land sustainability in Usangu Basin-Tanzania. *Heliyon*, 7(8), e07745. <https://doi.org/10.1016/j.heliyon.2021.e07745>
- Mng'ong'o, M.,** Munishi, L. K., Blake, W., Ndakidemi, P. A., Comber, S., & Hutchinson, T. H. (2021). Characterization of soil phosphate status, sorption and saturation in paddy wetlands in Usangu basin-Tanzania. *Chemosphere*, 278, 130466. <https://doi.org/10.1016/j.chemosphere.2021.130466>
- Mng'ong'o, M.,** Comber, S., Munishi, L. K., Ndakidemi, P. A., Blake, W., & Hutchinson, T. H. (2021). Land use patterns influence the distribution of potentially toxic elements in soils of the Usangu Basin, Tanzania. *Chemosphere*, 284(July), 131410. <https://doi.org/10.1016/j.chemosphere.2021.131410>
- Mng'ong'o, M.,** Munishi, L. K., Ndakidemi, P. A., Blake, W., Comber, S., & Hutchinson, T. H. (2021). Accumulation and bioconcentration of potentially toxic metals in two phases from agricultural soil to plants in Usangu agroecosystem-Tanzania. *Heliyon*, 7(7), e07514. <https://doi.org/10.1016/j.heliyon.2021.e07514>
- Mng'ong'o, M.,** Munishi, L. K., Blake, W., Comber, S., Hutchinson, H., & Ndakidemi, P. A. (2022). Towards sustainability: Threat of water quality degradation and eutrophication in Usangu agro-ecosystem Tanzania. *Marine Pollution Bulletin*, 181(July), 113–909. <https://doi.org/10.1016/j.envc.2021.100259>

## 2. Poster presentation

**Marco Mng'ong'o**, Patrick A. Ndakidemi, Linus K. Munishi, William Blake, Sean Comber, Thomas H. Hutchinson. (2020). Assessment of Pollution risk in agro-ecosystem for sustainable production in Southern Highland Tanzania. **9<sup>th</sup> International Conference on Agro-Ecology, 11-12 October 2020, Arusha-Tanzania**