PRODUCTION OF BIOGAS AS A WASTE MANAGEMENT OPTION FOR TEXTILE EFFLUENT SLUDGE: A CASE STUDY OF THE A TO Z TEXTILE MILLS LTD

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ABSTRACT

Textile effluent sludge management is becoming a major environmental management issue in many agro-processing industries throughout Africa. This is mostly due to the limited and ineffective means of management. This research explored the potential of producing biogas as a strategy for reducing the on-site accumulation of textile effluent sludge. The co-digesting of the textile effluent treatment plant (ETP) sludge with substrates such as sewage treatment Plant (STP) sludge, cow dung (CD), and sawdust, was investigated as the main approach for the anaerobic digestion (AD) process. ETP sludge and STP sludge were collected from A to Z Textile Mills Ltd factory and a complete characterization was made in triplicate for essential parameters, namely chemical ogygen demand (COD), biological oxygen demand (BOD), alkalinity, volatile fatty acids (VFAs), carbon to nitrogen ratio (C/N ratio) and heavy metals. Sludge mixtures were analyzed before and after digestion. Biogas production was tested for 30 days at different mixing ratios (4:0, 3:1, 1:1, 0:4). A laboratory-scale reactor was assembled for the experiments. High biogas yield was achieved from the co-digestion of ETP sludge and STP sludge at a mixing ratio of 3:1, 1:1, and 1:3, and methane content was, respectively, 87.9%, 68.9%, and 69.5% of the gas composition. Results from the current study provide relevant information to improve the production of biogas from ETP sludge through co-digestion and various pretreatment methods.

Keywords: anaerobic digestion, biogas, sludge management, textile sludge, wastewater treatment plant.

DECLARATION

I, Jean Gildas Tapsoba do hereby declare to the Senate of The Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has not been submitted nor being concurrently submitted for any degree award in any other institution.

Mr. Jean Gildas Tapsoba Date

Name and Signature of Candidate

The above declaration is confirmed by

Dr. Hans C. Komakech Date

Name and Signature of Supervisor 1

Prof. Revocatus Machunda Date

Name and Signature of Supervisor 2

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CERTIFICATION

The undersigned certify that the dissertation entitled “Production of biogas as a waste management option for Textile Effluent Sludge: A Case study of the A to Z Textile Mills Ltd.” is an authentic work done under their supervision, and recommend its acceptance in partial fulfillment of the requirement for the degree of Masters of Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology.

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DEDICATION

I am dedicating this work to my parents, Jean-Paul Tapsoba and Mariam Zoungrana, family and friends who believed in me and supported me during the entire program.

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LIST OF ABBREVIATIONS AND SYMBOLS

AD	Anaerobic Digestion
ANOVA	Analysis of Variance
BOD	Biological Oxygen Demand
CD	Cow Dung
COD	Chemical Oxygen Demand
EC	Electrical Conductivity
ETP	Effluent Treatment Plant
HRT	Hydraulic Retention Time
ICP-MS	Inductively Coupled Mass Spectrometry
MEWES	Materials Energy Water and Environmental Science
NM-AIST	The Nelson Mandela African Institution for Science and Technology
STP	Sewage Treatment Plant
TDS	Total Dissolved Solids
TS	Total Solids
VS	Volatile Suspended Solids
WESE	Water Environmental Science and Engineering
WWTPs	Waste Water Treatment Plants
VFAs	Volatile Fatty Acids

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

The management of industrial wastewater remains a major challenge in Sub-Saharan Africa (Wang *et al.*, 2014). For most countries, only a small fraction of urban wastewater is being treated through waste stabilization ponds, which comprise of series of ponds stabilizing organic matter through biological processes. However, most of these ponds are not designed to receive industrial wastewater because of toxicity to interfere with important microorganism in the biological treatment process. As a result, most industries are forced to construct their industrial effluent treatment plants. Textile processing industries often use dyes and bleach agents which require a huge amount of freshwater resulting in the production of toxic wastewaters (Jahagirdar *et al*., 2013). This type of wastewater is a challenge because of its negative environmental impacts if discharged untreated. In places where the local authority's capacity to enforce environment regulation is weak, most industries often discharge their effluent untreated into the surrounding lands and surface waters. However, due to increased public awareness on this matter, most African countries have adopted strict environmental pollution control measures and laws to prevent the discharge of untreated wastewater.

The production processes in textile industries require huge volumes of high-quality water and generate considerable volumes of wastewaters (Srebrenkoska *et al*., 2014). The processing utilizes a variety of chemicals and the main contaminants in the wastewaters came from dyeing and finishing processes (Ciubota-Rosie *et al.*, 2008). The wastewaters from printing and dying entities should be treated before discharging into the environment given the fact that they contain chemicals and residues of reactive dyes (Babu *et al*., 2007). The foremost pollutants in textile wastewaters are color, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), fats, oil, high suspended solids, acidity, and other soluble substances (Tüfekci *et al*., 2007).

There is no single appropriate treatment method for any kind of wastewater. Many methods such as biological, physical, and chemical treatment should be applied depending on the nature of pollution (Srebrenkoska *et al*., 2014). Recent studies also showed that physicochemical precipitation was efficient in reducing dye concentration, turbidity, COD, and also contributes to reducing fouling. Moreover, biological treatment is efficient for COD and DOC removal but not for mineral parameters (Boda, 2017). Recently, stakeholders have shown interest in ecologically friendly wet-processing techniques, due to the increase of consciousness of environmental problems. Nowadays, many textile factories have installed an effluent treatment plant (ETP) for textile wastewater treatment before disposal. As a result of wastewater treatment, huge quantities of textile effluent sludge are being generated and are affecting environmental quality. Approximately 1 – 10 tonnes of textile sludge can be produced daily by an industry that uses about 50 m^3 of freshwater hourly (Karthik & Rathinamoorthy, 2015). During the treatment, process sludge is generated and contains organic and inorganic matter, including heavy metals such as Cr, Fe, Cd, Cu, Zn, etc., which are toxic to both human health and natural environment. Pollutants in the sludge come from varieties of dyes and chemicals used during the textile processing (Guha *et al*., 2015). Textile effluent sludge management remains a challenge for many textile industries despite the existence of several management options. Numerous management option such as sanitary landfilling, incineration, brick fabrication, and aquatic disposal has been previously used (Guha & Morshed, 2015).

1.2 Statement of the Problem

Proper management of textile effluent sludge is a major challenge faced by many textile industries despite the existence of wastewater treatment plants. The biological treatment of the textile effluent follows an activated sludge process. However, this process results in the accumulation of a large quantity of sludge due to the excess of biomass, which has not been degraded during the process (Karthik & Rathinamoorthy, 2015). The current practice in sludge management is the disposal of sludge in the treatment plant sites, but also in the protected areas while waiting for appropriate dumping sites or reuse. Textile effluent sludge is characterized by a mixture of heavy metals, organic, and inorganic matters (Guha *et al*., 2015). Therefore, inappropriate handling and management of this sludge can lead to chronic environmental impacts and can affect the human, plant as well as animal health (Delelegn, 2018).

Many methods have been used in the textile effluent sludge management. These methods include incineration, landfilling, composting, brick fabrication, and biogas production. The method of Landfilling may affect surface and groundwater due to fluids conveying toxic tons of metals, nitrates, and pathogens (Karthik & Rathinamoorthy, 2015). The incineration technique is found to be an expensive method because of the high costs required in construction and maintenance. Moreover, this technique produces contaminated ash and releases pollutants in the atmosphere (David Jr *et al*., 2016). Due to heavy metals concentration in the textile sludge, composting is found to be harmful to plants because plants get nutrients as well as toxics matters from the compost (Guha *et al*., 2015).

1.3 Rational of the Study

To ensure an efficient biodegradability of textile effluent sludge, it is necessary to find a carbon-rich substrate for co-digestion experiments. Materials such as cow dung, food waste, sawdust, sewage sludge are known to be a good substrate for anaerobic digestion (AD), given their high carbon to nitrogen ratio (C/N ratio) and their high organic matter content. Most of these substrates are readily available. Additionally, textile sludge treatment using AD technology can be improved using various pretreatments techniques such as thermal hydrolysis and chemical treatment. These methods are efficient in reducing treatment time and enhancing sludge biodegradability.

1.4 Objectives

1.4.1 General Objective

The main goal of this study is to evaluate the biogas production potential from textile effluent sludge.

1.4.2 Specific Objectives

To achieve the above general objective, the research sought to pursue the following specific objectives:

(i) To determine the physicochemical composition of the textile effluent treatment plant sludge.
(ii) To investigate methods for improvement of biogas yield by co-digesting the textile sludge with substrates that are rich in organic matter.

1.5 Research Questions

Based on the problem context cited above, this study will be directed by the following questions:

(i) What are the major components of the textile sludge?

(ii) To what extent the co-digestion of the textile sludge with substrates can enhance the efficiency of biogas production?

1.6 Significance of the Study

The present study aimed at finding a suitable and cost-effective solution for textile effluent sludge management through biogas production. Thus, biogas production from textile sludge will act as a sustainable waste management strategy with several benefits. Firstly, producing biogas using textile effluent sludge can be qualified as a waste-to-energy conversion which will reduce the sludge dumping into lands, and provide an alternative source of energy (Karthika & Bindu, 2017). Secondly, textile effluent sludge recycling and reuse is an environmentally friendly method, which will contribute to reducing the concentration of pollutants in the raw sludge, leading eventually to environmental protection and therefore, public health protection. Finally, this study is important because the results will serve as a baseline for further research and will help in establishing a guideline for effluent sludge management from textile industries.

1.7 Delineation of the Study

Several methods are used for sludge treatment and management. The proposed treatment method from this study is not intended to be a standard option for sludge management. Rather, the study was focused in implementing a method that is best suited to the A to Z textile mills Ltd. Since the company also has a sewage treatment plant and its treatment process also generates large quantities of sewage sludge, which was dumped within the treatment plant site while waiting for an appropriate treatment option. Thus, sewage sludge was used as the main co-substrate to improve the AD process of textile sludge. However, toxic metals contained in the sludge cause the limitation of the efficient treatment of sludge through AD. Heavy metals behavior during the AD has not been studied since the study focused on improving the biodegradation process of textile sludge using co-digestion methods.

CHAPTER TWO

LITERATURE REVIEW

2.1 Effluent Treatment in Textile Processing Industries

The ever-increasing Textile processing industries generate huge volumes of very colored wastewater due to low uptake of dyes by the fabrics. The wastewater generated represents a major environmental challenge when discharged without appropriate treatment. Textile wastewater is known to have high COD, BOD, TDS, salts, and the presence of reactive dyes. The discharge of textile wastewater with high BOD or COD into water bodies creates anaerobic conditions due to the depletion of dissolved oxygen. Such conditions can produce smelling compounds like hydrogen sulfide and can adversely affect the biological activities in the receiving water bodies (Kumar *et al*., 2014). Moreover, dye effluents are adversely affecting the environment, as well as living organisms. Therefore, textile wastewater should be treated before discharge to diminish the risks. Textile wastewater treatment includes pretreatment, primary treatment, chemical and physical separation treatment, secondary treatment, tertiary treatment, and sludge treatment and disposal methods as described in Fig. 1 (Holkar *et al*., 2016; Katheresan *et al*., 2018). Mechanisms of the treatment can be combined in various ways following Rasheed and Kavitha (2014):

(i) A biological treatment plant including screening, potential of hydrogen (pH) monitoring, equalization, aeration, and settling. The biological treatment can meet and an efficient requirement for BOD, TSS, pH, grease, and oil. It is necessary to apply a pretreatment method because of the toxicity of effluent compounds that may affect the microorganisms.

(ii) A physicochemical treatment which is sometimes combined with biological treatment. The physicochemical treatment includes screening, pH monitoring, equalization, chemical storage tank mixing unit, flocculation unit, settling, and sludge dewatering.

(iii) A reed bed, which can be combined with other treatment processes or used with a settling tank. The reed bed is a natural treatment method of effluent which contributes to reducing treatment, operation, and maintenance costs. The reed bed is responsible for color removal and heavy metals, and, COD reduction. However, these treatment options cause an increase in dissolved oxygen.

Several methods are applied for treating wastewater including dye removal. However, these methods present a disadvantage in which the production of secondary pollutants, another challenge to the environment (Katheresan *et al*., 2018).

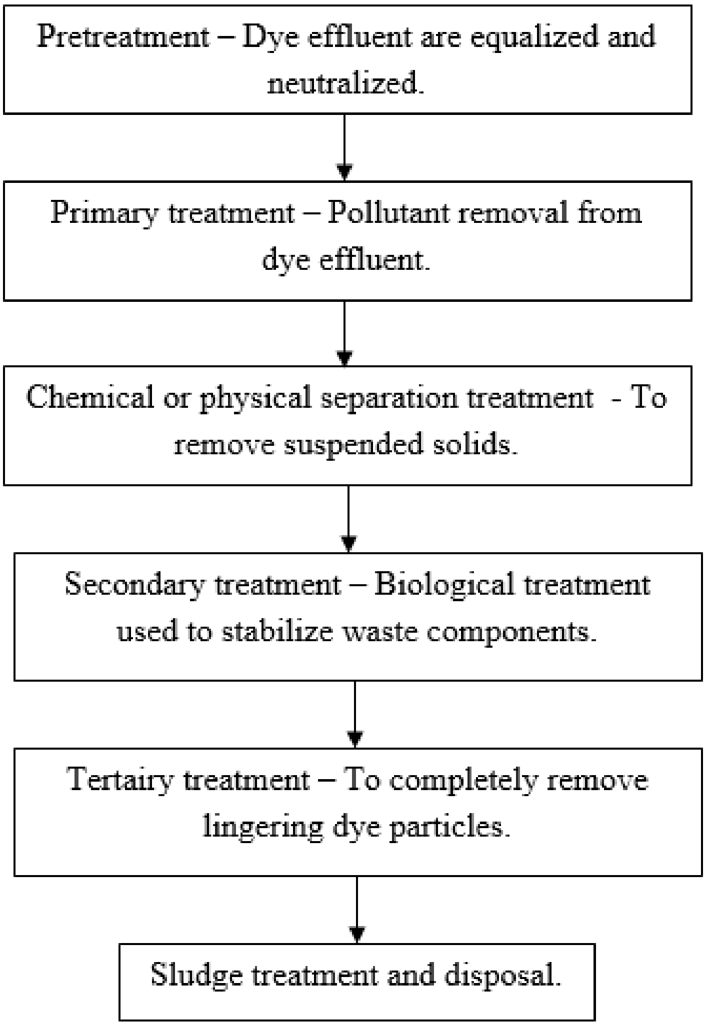


Figure 1: Traditional wastewater treatment system

2.2 Current Sludge Management in Textile Processing Industries

Sludge management from textile effluent treatment plants is more and more a major challenge. Large volumes of sludge are generated annually as a result of wastewater treatment as described in Fig. 2 (Carrère *et al*., 2010). Also, the produced sludge is generally dumped into the surrounding lands without any treatment. This practice eventually leads to environmental pollution (Fig. 3). Because of poor sludge management methods, the dumped sludge gets in contact with rain and floods, which adversely affect the surrounding lands and water bodies (Anwar *et al*., 2018). Moreover, these wastes are responsible for causing biological, physical, and chemical damages to the aquatic environment. Consequently, public health including wildlife, livestock, fish, and other biodiversity is threatened due to contaminations of salts, inorganic, and toxic metals in the textile sludge (Rahman *et al*., 2017). The sludge is highly contaminated and contaminants such as chemicals and heavy metals from the bleaching processes and dyes. Some sludge characterization undertaken in Ethiopia has shown that heavy metals in the sludge were total phosphorous (5.3 mg/kg), lead (22.70 mg/kg), cadmium (4.970 mg/kg), and the moisture content was 17.99%. The recorded pH was 9.09 and alkalinity 473.3 mg/kg (Delelegn, 2018). These heavy metals including chromium, arsenic have various adverse effects on human health. It was reported to be the cause of different skin diseases. Also, it can lead to cancer (Anwar *et al*., 2018).

Other sludge management techniques include landfills, incineration, composting, underwater disposal, etc. However, these management options have some limitations (Martínez-García *et al*., 2012). Landfilling adversely affects the environment through the soil, water, and air pollution. The leaching behavior of raw sludge from the ETP is very high, resulting in groundwater contamination. Landfills are responsible for uncontrolled landfill gas production such as carbon dioxide and methane. These compounds can be responsible for global warming (Iqbal *et al*., 2014).

The incineration technique requires a furnace, more support systems, fuels, and trained operators. Moreover, this technique constitutes a threat to the environment because of gas emission and ashes production. The incineration technique also requires a lot of precautions for its application due to potential fire it may cause (Anwar *et al*., 2018). The problem with landfills resides in the availability of landfill sites and incineration technique leads to the production of ash (Martínez-García *et al*., 2012). Composting is less preferred as a disposal method due to the high quantity of volatile organic matter, heavy metals, and the changing quantity of the textile sludge (Anwar *et al*., 2018).

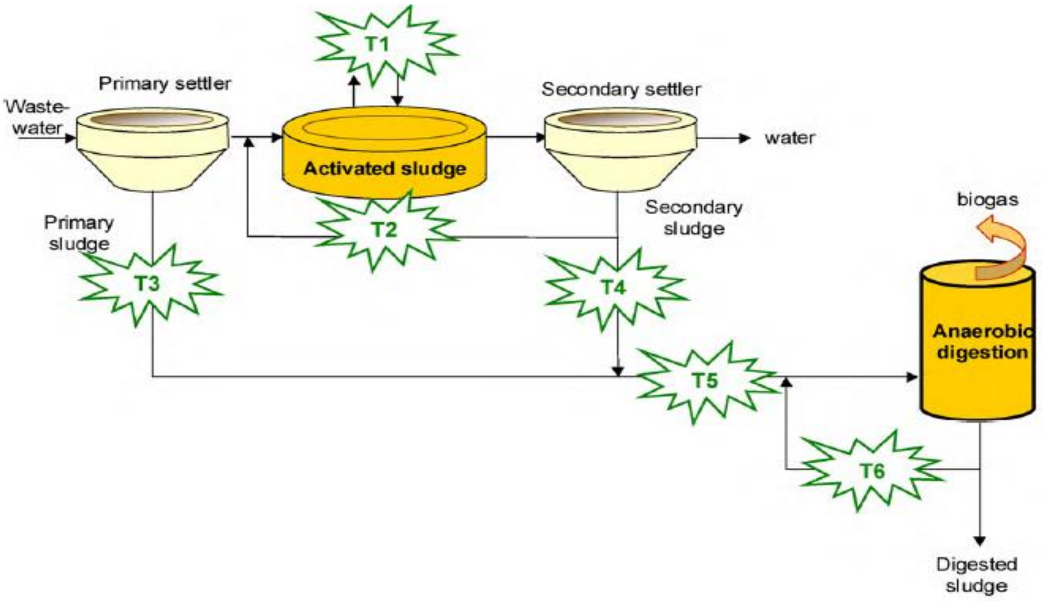


Figure 2: Sludge treatment locations in a traditional wastewater treatment plant

The activated sludge treatment process is represented by T1. The treatment on the activated sludge recirculation loop is represented by T2. The pretreatment of primary sludge before anaerobic digestion is represented by T3. The waste activated sludge pretreatment before anaerobic digestion is represented by T4. The mixed sludge pretreatment before anaerobic digestion is represented by T5. The treatment on the recirculation loop of anaerobic digester is represented by T6. The common trend with sludge management is its disposal within the treatment plant site while waiting for a proper management option.

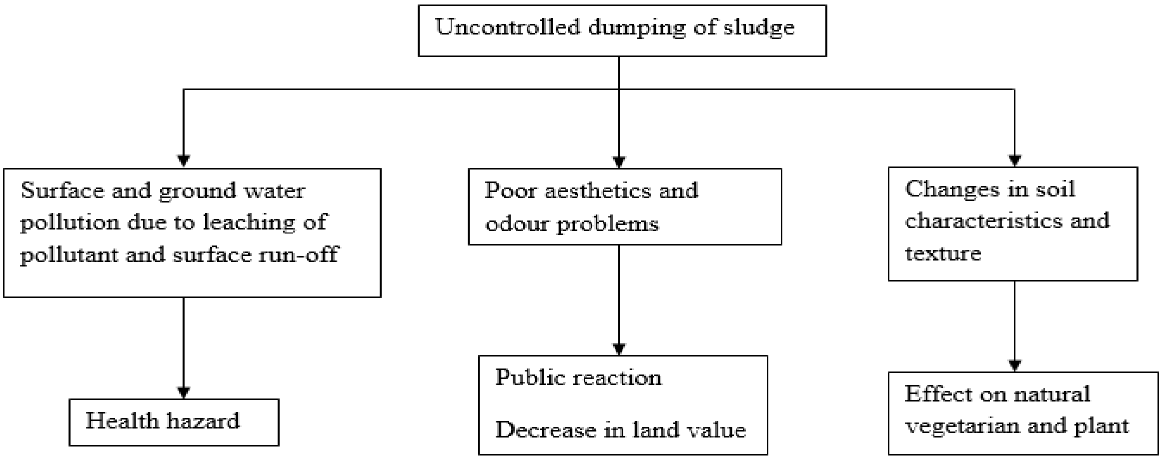


Figure 3: Environmental impacts due to poor management of textile ETP sludge (Karthik & Rathinamoorthy, 2015)

2.3 Review of the Anaerobic Digestion and Application for Industrial Wastewater

The AD is a commonly used biological wastewater treatment process, and it is also a good method for energy production (Meegoda *et al*., 2018). The AD process involves a biological degradation of organic matters in the absence of oxygen, resulting in the production of biogas. It is a low-cost process that transforms organic matter into biogas especially when the wastewater contains high Chemical Oxygen Demand (COD) (> 3000 mg/L). The COD concentration is an indicator of the organic content of the sludge (Al Yaqout, 2003). Wastewaters from textile de-sizing processes often contain organic matters such as starch, and polyvinyl alcohol (PVA), which are easily biodegradable (Holkar *et al*., 2016). Domestic wastewaters are a good substrate for the AD process and it is frequently integrated as part of waste stabilization ponds in urban areas (Mao *et al*., 2015; Kumar & Ankaram, 2019). Generally, the AD process occurs in four main steps (Bharathiraja *et al*., 2018) described as hydrolysis, acidogenesis, acetogenesis and methanogenesis (Fig. 4).

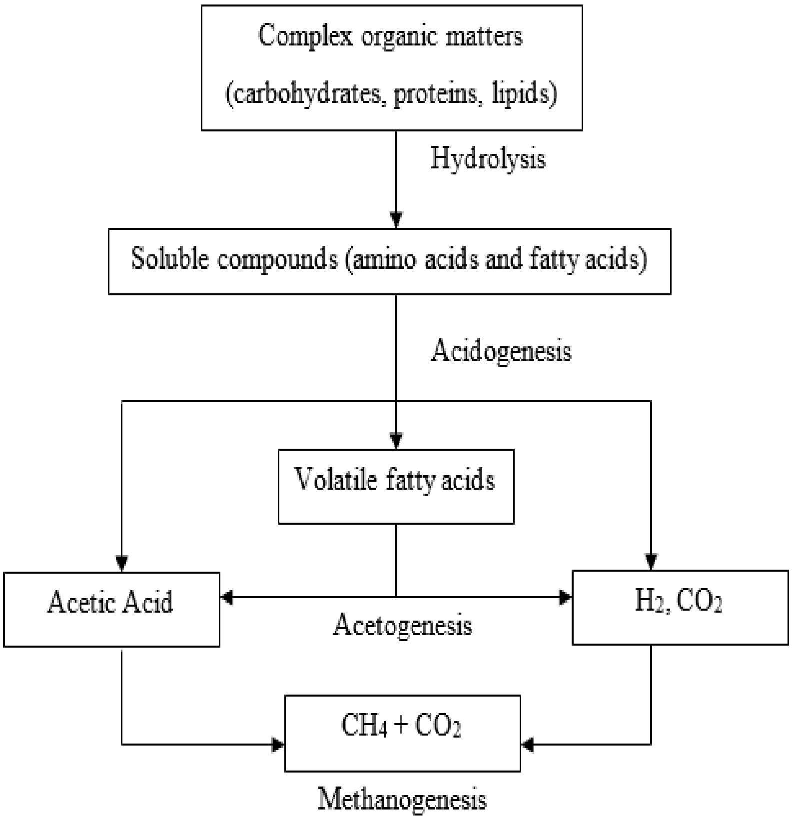


Figure 4: Anaerobic digestion process steps

During hydrolysis, organic matters such as carbohydrates, proteins, nucleic acid, and lipids are hydrolyzed into soluble compounds, fatty acids, and amino acids. During acidogenesis, compounds such as hydrogen, alcohols, carbon dioxide, and volatile fatty acids (VFAs) are produced. After acidogenesis, alcohols and organic acids are transformed by acetogens into carbon dioxide, hydrogen, and acetate. Acetogenesis is followed by the methanogenesis, which is the final step of the AD process. During the methanogenesis, methane is produced by methanogens following two different phases: acetate is degraded into carbon dioxide and methane by acetotrophic bacteria, and hydrogen is consumed by hydrogenotrophic methanogens resulting in the production of produce methane.

In this final step, the acidification products are converted into methane following equations i – v (Li *et al.*, 2019):

(i) $CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$

(ii) $HCO_3^- + H^+ \rightarrow CH_4 + 3H_2O$

(iii) $4CH_3OH \rightarrow CO_2 + 2H_2O$

(iv) $4HCOO^- + 2H^+ \rightarrow CH_4 + CO_2 + 2HCO_3^-$

(v) $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

Microorganisms, particularly methanogens are fragile to changes during the AD process, and conditions such as toxicity, heavy metals content, nutrients, pH and temperature can affect the process. The inhibitory compounds, existing in sludge and are found to cause the failure of the AD process (Kumar, 2013). Heavy metals in sludge are known to have an antagonistic effect on the overall process of AD (Abdel-shafy & Mansour, 2014). Trace elements such as manganese, iron, and molybdenum are less toxic and important for the process. However, antimony, lead, mercury, uranium, arsenic and uranium are very toxics and their biological role is very limited (Kumar, 2013). Various methods are widely applied to improve the microbial activities during AD and therefore, avoid the process failure. Studies have reported that co-digestion with substrates rich in carbohydrates can enhance biogas yield compared to mono-digestion of single substrates. Also, substrates decomposition can be improved trough pretreatment techniques such as thermal, chemical, enzymatic, and mechanical (Zhang *et al.*, 2017; Bharathiraja *et al.*, 2018).

Gnanapragasam *et al.* (2011) conducted batch reactor experiments using the AD process for treating textile dye effluent to reduce COD and eliminate color. The setup was composed of a reactor of 5L capacity, for synthetic textile dye and starch wastewater combined treatment at different mixing ratios of 20:80, 30:70, 40:60, 50:50 and 60:40. They reported that the optimum ratio was 30:70 and the percentage reduction of COD and color were respectively 81.0% and 87.3%. The authors concluded that the results from the batch studies can be used to design a large-scale continuous reactor for combined textile dye and starch wastewater treatment under the same conditions.

Punzi *et al*. (2015) used a system composed of an anaerobic biofilm reactor followed by ozone treatment. They revealed that the anaerobic treatment was able to achieve removal efficiency of 70% for COD (hydraulic retention time was 3 days for AD). Treating the effluent using the ozonation method for 6 min was able to further reduce organic matter in the effluents. Toxicity was also found to be 20 times lower than that of the initial level. Moreover, aromatic matters of effluent were reported to be degraded by ozone. It was recommended to use the ozonation method as a post-treatment system after anaerobic digestion as it enhances the reduction of refractory compounds and toxicity.

Lin *et al*. (2017) investigated the performance of granular activated carbon (GAC) adsorption, combined with AD under mesophilic conditions, and microalgae scenedesmus species cultivation. Experiments were conducted using laboratory-scale reactors for the treatment of textile wastewater as well as regenerating algae biomass and biogas. The wastewater was pre-treated using the GAC to limit AD process inhibition and the microalgae were used to further treat digester effluent. The combined system was able to produce methane, ethanol energy, and total hydrogen, at a rate of 16.9 kJ/ (L·d). Also, high pollutants elimination efficiencies were obtained for chemical oxygen demand (COD) 89.5 %, color 92.4 %, organic acids 94.7 %, and carbohydrates 97.4 %. However, the authors have found that reducing COD, VFAs use, and color removal efficiencies depend on the effluent initial concentrations. Thus, for textile dye effluent treatment, a flow rate of 1000 m^3/d is recommended by the authors as a conceptual treatment process. Methane production as well as biomass is predicted to be 2.07×10^7 kJ/d and 9800 kg/ 7 d (7 days), respectively.

There is extensive research on the application of AD for industrial wastewater treatment and the outcomes appear to be satisfactory. However, the secondary pollutant (sludge) from this treatment process is another concern for textile wastewater post-treatment. There is a lack of systematic studies on textile sludge treatment, especially the application of AD technology. Hence, this study was oriented towards the application of AD on textile sludge. Finally, the process was optimized trough co-digested with substrates such as Sawdust, and CD followed by a thermochemical treatment of the mixtures. The developed treatment scheme was tested in the laboratory.

2.4 Factors Affecting Biogas Production from Textile Effluent Sludge

Several factors can cause the failure of the AD process. Various microorganisms are involved in the AD process. These microorganisms need a balanced environment to generate biogas from the feedstock. Abrupt changes in the environment can adversely affect the microbial activities, therefore, cause the shutdown of the AD process (Pramanik *et al.*, 2019). To ensure an effective and efficient AD process, it is necessary to monitor parameters such as VFAs, pH, C/N, the hydraulic retention time, and temperature, which adversely affect the AD process (Kainthola *et al.*, 2019).

2.4.1 Temperature and Hydraulic Retention Time (HRT)

Temperature is a key parameter for the evolution of the microorganisms during the AD and is used to differentiate the degradation stages. There are three operational ranges of temperature for AD. The thermophilic (55–70 °C), mesophilic (20–45 °C), and psychrophilic (below 20 °C) (Kainthola *et al.*, 2019). It is found that the mesophilic temperatures are more stable compared to thermophilic ones due to microbial activities that are microorganisms that favor mesophilic temperatures to thermophilic (Siddique & Wahid, 2018). However, thermophilic environments (55 °C) can speed up the AD process. Also, such conditions can improve pathogen elimination during the anaerobic phase. The challenge with thermophilic conditions resides in heating the digester to higher temperatures (Jain *et al.*, 2015).

The retention time is defined as the average time spent by the substrate in the biodigester (Kainthola *et al.*, 2019). Microbial activities can be inhibited under controlled HRT. Moreover, long HRTs can cause the inactivity of the microorganisms, whereas short HRTs are recommended to maximize biogas yield (Siddique & Wahid, 2018).

2.4.2 pH and Volatile Fatty Acids (VFAs)

The pH is a factor that changes over time during the AD process. The pH is around 6 during the initial stage, which is the acidic formation step of the fermentation process, and carbon dioxide is produced. After 2 – 3 weeks, the pH increases because the volatile acid is consumed and methane gas is generated (Jain *et al*., 2015). It has been reported that a pH ranging between 6.8 and 7.2 is ideal for biogas production in AD. However, the methanogens, microorganisms responsible for methane production, are found to be pH sensitive and prefer a pH around 7 (Hagos *et al*., 2017).

The VFAs are principally composed of valeric acid, butyric, propionic acid, and acetic acid. VFAs are intermediate products formed during the AD process. During the process, the acetogens and methanogens transform the VFAs into carbon dioxide and methane. However, VFAs accumulation can lead to a diminution of pH, and eventually cause the failure of the AD process (Zhang *et al*., 2014). At concentration ≥ 2 g/L, cellulolytic activity is inhibited by VFAs (Kondusamy & Kalamdhad, 2014).

2.4.3 Carbon-Nitrogen Ratio

The performance of AD can be considerably affected by the carbon-nitrogen (C/N) ratio. For biogas production, it is important to obtain an optimum C/N ratio because the anaerobic microorganisms need an appropriate nutrient balance for their growth. A C/N ratio ranging from 20 – 30 is considered a suitable condition for AD (Zhang *et al*., 2014). The C/N ratio can be enhanced through the co-digestion of organic mixtures (Khalid *et al*., 2011). However, improved C/N ratio could lead to the releasing of high total ammonia nitrogen or high VFAs accumulation in the reactor, which could cause AD process inhibition (Li *et al*., 2011).

2.4.4 Heavy Metals

Heavy Metals are identified as metalloids of density larger than 5 g cm^{-3}. Generally, Heavy metals are linked with toxicity level although some of these metals are important and needed by microorganisms when they are in low concentration. In our modern society, toxicity of heavy metals and their accumulation in the food chain are a major environmental concern. In the AD process of substrate, heavy metals play a key role in biochemical reactions. Depending on their concentration, they can have stimulatory biochemical effects on the AD process. Metal elements such as heavy metal ions (Zn, Ni, Co, Cr, Cu, etc.), and light metal ions (Al, Ca, Na, K, Mg) are needed by anaerobic bacteria.

2.5 Sludge Pretreatment to Improve Biogas Production

To ensure an effective sludge treatment as well as an effective biogas production from sludge it is indispensable to apply some pretreatment methods before AD. Primary sludge from ETP is readily degradable and does not necessarily require a pretreatment.

However, activated sludge has low degradability but can be enhanced by improved rates (Carrère *et al*., 2010). During the AD, hydrolysis is considered a rate-limiting step. Thus, applying various pretreatment methods can disintegrate the sludge, therefore, speed up the rate-limiting hydrolysis and enhance the AD process efficiency (Zhen *et al*., 2017). Sludge pretreatment methods are presented in Table 1 and include mechanical, biological, thermal, and chemical (Jain *et al*., 2015).

2.5.1 Chemical Pretreatment

This pretreatment is a cost-effective treatment method and is used to maximize the biodegradation of complex materials and organic matters through means of strong acids, alkalis, bicarbonates, or peroxide (Gunes *et al*., 2019). Moreover, the chemical pretreatment is found to be efficient to improve the solubility of the organic material in the cells by hydrolyzing the membrane and cell wall. Reagents are used to deform membrane and cell wall, thus leading to the accessibility of organic matters of the sludge for enzymatic activities (Zhen *et al*., 2017). Chemical pretreatment can be acid or alkaline. Alkaline pretreatment is usually combined with a thermal pretreatment (Hanjie, 2010). The chemical pretreatment effect is dependent on substrates characteristics and the type of methods applied. However, chemical pretreatment is not adapted for easily decomposable substrates with high carbohydrates content (Ariunbaatar *et al*., 2014).

2.5.2 Biological Pretreatment

This treatment is composed of both aerobic and anaerobic methods. Moreover, bacteria such as hydrolytic bacteria or enzymes such as lipase, peptidase, carnohydrolase, are added to the AD system. It is found that enzymatic hydrolysis, can speed up the decomposition of complex organic material. Various enzymes such as enzyme complex, beta-glucosidase, betaglucanase, cellulase, lyticase, alpha-amylase lipase, protease, and papain have been used for the AD process (Gunes *et al*., 2019).

2.5.3 Mechanical Pretreatment

It is the process by which solid elements of the substrates are disintegrated, increasing the specific surface area and release of the cell compounds. The increased surface area contributes to enhancing the AD process by providing contact between the microorganisms and the substrate (Ariunbaatar *et al*., 2014).

2.5.4 Thermal Pretreatment

Thermal pretreatment is responsible for cell membranes' disintegration, resulting in organic compounds solubilization. Moreover, this pretreatment method leads to pathogens removal, improves dewatering efficiency, and reduces digestive viscosity. Table 1 presents the effect of various thermochemical pretreatment techniques on CH_4 production.

For the AD process improvement, several temperatures (50 – 250 °C) have been widely applied (Ariunbaatar *et al*., 2014). Studies have reported that better degradation is obtained from thermal treatment at 190 °C and at 135 °C, total COD removal, lipids, carbohydrates, and proteins were efficiently achieved, and better methane yield is obtained. Thermal pretreatment can enhance the hydrolysis, which is the rate-limiting step of the AD process and reduce the retention time. Biogas enhancement through thermal pretreatment is linked to COD solubilization (Kondusamy & Kalamdhad, 2014).

Table 1: Effect of various thermochemical pretreatment methods on CH_4 production (Hanjie, 2010)

Sludge	Treatment conditions	AD conditions	Results
Activated sludge (43 $g.L^{-1}$)	175ºC 60 min 300 meg NaOH. L^{-1}	35 ºC 25 days Batch	CH_4 production is increased (+62%)
Activated sludge (30 $g.L^{-1}$)	55 ºC 240 min 45 meg NaOH. L^{-1}	35 ºC 20 days Batch	CH_4 production is increased (+88%)
Activated sludge (17 $g.L^{-1}$)	130 ºC pH: 10 60 min 1.65 g KOH. L^{-1}	35 ºC 25 days CSTR	CH_4 production is increased (+75%)

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Site

Sludge collected from A to Z Textile Mills Ltd in Arusha, Tanzania was used for this study. The company has installed its effluent treatment plant where wastewater from the factory undergoes an activated sludge process (Fig. 5).

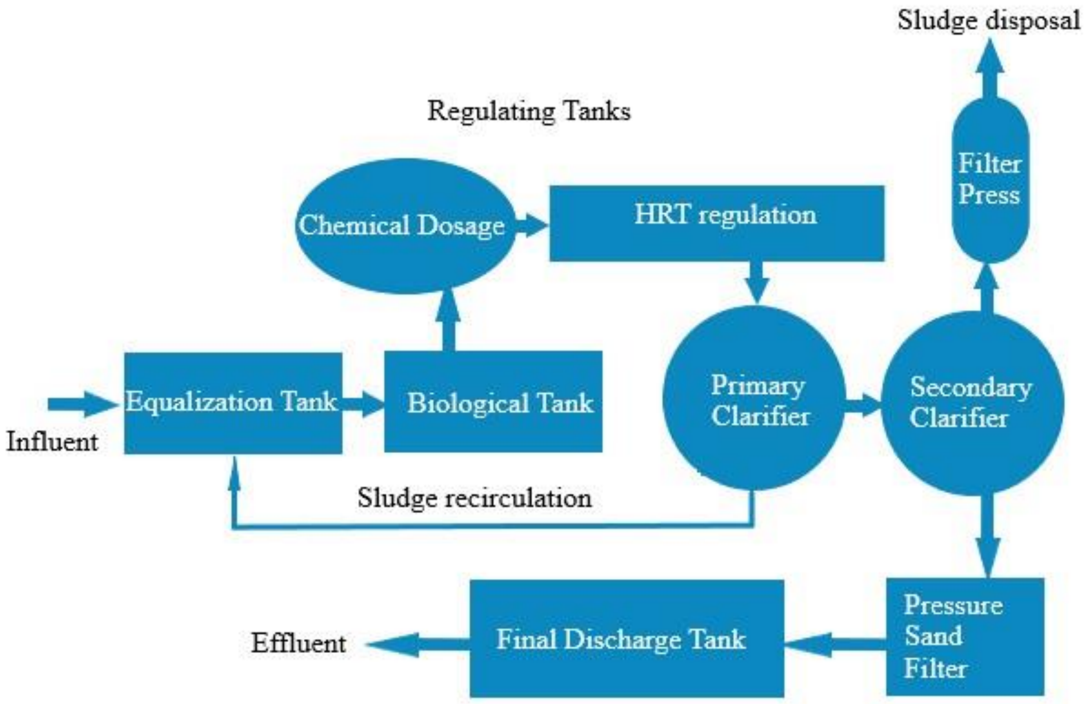


Figure 5: Flow diagram of textile effluent treatment plant (ETP)

The system is composed of an equalization tank, a biological tank, regulation tanks, secondary tanks, a pressure sand filter, and a final discharge tank:

(i) Equalization tank: wastewater from the textile dying process is collected in the equalization tank. A blower is used at this step of the treatment process to inject air in the tank. The addition of air enhances the aeration and complete mixing of the influent wastewater. The pH is checked every 2 hours and it is maintained between 7.5 and 8 using hydrochloride acid (3.01). A pH lower than 6.5 will forbid the sludge from settling. In extreme cases, Caustic is added to maintain the pH.

(ii) Biological Tank: the biological treatment of the wastewater is performed under aerobic conditions. The tank is also aerated and mixed using a blower. Color removal is done using Microplus, which is a color removal coagulant (50 g/ 1000L if the color is light and 100 g/ 1000L if the color is dark). For microorganism enhancement, cow dung, urea, and fertilizer such as Diammonium Phosphate (DAP) are used.

(iii) Regulation tanks: It is composed of a chemical dosage tank and Hydraulic Retention Time (HRT) regulating tank. Hydrated lime is dosed at this step to enhance the reduction of oxidizable organic pollutants but also for clarification purposes through coagulation and flocculation of particles.

(iv) The secondary tanks: it comprises the primary clarifier and the secondary clarifier. In the secondary clarifier, coagulation and flocculation method is used to enhance decolorization. However, this method has some limitations due to low decolorization efficiency, but also the production of bio-sludge (Holkar *et al.,* 2016). Further color removal is also performed, using Microplus dosed at around 10 g/ 1000L for light shade and 20-25 g/ 1000L for a dark shade. Along with this, a polyelectrolyte solution Animole 2030 is dosed at around 2 g/ 1000L in the Flocculator Tank, to help in particle bridging and compaction of the sludge. An electrical coagulation (EC) machine is used to generate heat that will enhance the color removal from the water. A polymer is also dosed to enhance the flotation of the sludge. The produced sludge from the secondary clarifier is transferred to the Filter Press for dewatering purposes and discharge.

(v) Pressure sand filter (PSF): the effluent is directed to the pressure sand filter for final treatment, then conveyed in the final discharge tank for reuse.

Approximately 234 m^3 of effluent is being treated daily. One of the major challenges with the current treatment process is the large quantity of sludge produced, which is being dried and stored in bags onsite. Due to its pollution risks, A-Z currently does not have a suitable solution for sludge disposal.

During this research, sludge samples were collected from the treatment units at different stages. Wet sludge and dewatered sludge were collected respectively from the final discharge tank and the filter press (Plate 1). Sewage sludge was collected at the same site, from the

Sewage treatment plant located within the industry. The sludge was packed and stored in polyethylene bags for various laboratory analyses.

Plate 1: Final Discharge Tank (a) and the Filter Press (b)

3.2 Characterization of Effluent Treatment plant Sludge and Mixed Sludge

Sludge physical parameters such as electrical conductivity (EC), Total Dissolved Solids (TDS), pH, and temperature were measured onsite and, in the laboratory using HANNA Instruments Multiparameter (RI, U.S.A.) according to manufacturer's instructions.

Selected physicochemical parameters were measured, according to Standard methods if applicable. Method 5220D for measurement of COD, Method 2540G for measurement of total solids (TS) and volatile suspended solids (VS), dried at 105 °C and 505 °C respectively (APHA, 1999). For BOD, samples were incubated for five days at 20 °C in the Incubator (model OxiTop Box), and the C/N ratio was determined using the Thermo Scientific FLASH 2000 HT Elemental Analyzer.

Selected Heavy Metals such as Zinc (Zn), Nickel (Ni), Cadmium (Cd), Chromium (Cr), Iron (Fe), Copper (Cu), Lead (Pb), and Mercury (Hg) were analyzed using an Atomic Absorption Spectrophotometer (model WFX-210). Volatile Fatty Acids were determined using a Gas Chromatographic method. The efficiency of pollutants elimination for each sample was determined using the following formula (Eq. vi):

(vi) $\frac{Ci-Cf}{Ci} \times 100$

Where C_i and C_f represent is the initial and final concentration of pollutants in the samples respectively.

3.3 Design of Lab-scale Batch Reactor

A simple lab-scale biogas reactor (Fig. 6) was assembled in the NM-AIST laboratory and experiments were conducted under mesophilic (37 °C).

Temperature control was done using the Memmert Water Bath (type ONE 7). The reactor was constructed using an Erlenmeyer flask bottle (0.5 L), connected to a measuring cylinder (1 L). Another experiment was conducted to validate the biogas production and the reactor was up-scaled to a total working volume of 1 L. A plastic pipe was used to connect the reactor to the gas collector and parafilm was used to seal the Erlenmeyer flask’s outlet to prevent gas leakages. Biogas volume was assessed using the water displacement technique. The HRT was chosen to be 30 days and the series of experiments lasted for 122 days. Biogas volume was monitored daily and a biogas analyzer (model Biogas 5000, UK) was used to evaluate the methane content of the gas.

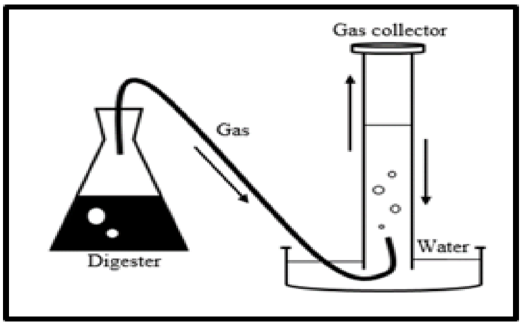


Figure 6: Diagram of the laboratory-scale biogas reactor

3.4 Co-digestion Experiments

A series of co-digestion experiments were conducted, using the textile effluent sludge and/or wastewater, as a strategy for textile waste management. Co-digestion is known for improving biochemical conditions, therefore increasing the biogas yield (Wang *et al.*, 2014). Selected parameters, including VS, pH, COD, TS, and BOD were analyzed for the different mixtures. In the first experimental setup, sewage sludge was selected as the main substrate to increase the organic content of ETP sludge, but also due to its availability. Karlsson *et al.* (2014) have reported that sewage sludge is a good base that can enable better nutrient and trace element balances. ETP sludge and STP sludge were mixed at different ratios 4:0, 3:1, 1:1, 1:3, 0:4 by volume, and 100 mL of raw water was added to sludge mixtures to have a total working volume of 500 mL.

3.5 Pretreatment Experiments

The second experimental setup explored various ways of optimizing biogas and methane production. Parameters such as pH, substrate type, alkali, and thermal pretreatment were selected for the optimization. Thus, two series of experiments were set as follow:

(i) ETP sludge + STP sludge at different mixing ratios (3:1, 1:1, and 1:3) + 50 g of cow dung (CD),

(ii) ETP sludge + STP sludge at different mixing ratios (3:1, 1:1, and 1:3) + 50 g sawdust.

Thermal hydrolysis conditions depend on time and treatment temperature. In the current study, high thermal hydrolysis of 170 °C was used for about 60 minutes. A 1L beaker and a hot plate were used for the heating process. The beaker was covered with aluminum paper to avoid water evaporation. The alkali treatment consisted of adding 3 g/L of NaOH to the sludge mixtures to maintain the pH between 6.5 and 7.5. The pretreated sludge was then used in the batch digestion described above. Nitrogen gas was flushed into the reactors to ensure better anaerobic conditions of the digesters.

3.6 Statistical Analysis

One-way analysis of variance (ANOVA) in Excel software was used to compare the differences in biogas yield among data obtained from anaerobic co-digestion of ETP sludge with different substrates at different mixing ratios. Statistical significance was set at a p-value < 0.05. All the graphs were plotted in Origin software version 9.5.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Effluent Treatment Plant Sludge and Sewage Treatment Plant Sludge Characteristics

The results of ETP sludge and STP sludge characterization are presented in Table 2. The current investigation found that ETP sludge was dark in color, with an aggressive odor. The sludge is found to be slightly alkaline with pH values between 8.4 and 9.6. The VS and TS were respectively 56.5 and 51.5 g/L. In STP sludge, VS and TS were respectively 75.5 g/L and 51.35 g/L. The C/N ratio was found to be higher in STP sludge and could balance the C/N ratio of the sludge mixture. The C/N ratio ranged from 10.46 to 11.27 for STP sludge and from 3.55 to 3.81 for ETP sludge. The BOD values ranged from 850 mg/L to 2250 mg/L for ETP sludge and from 1900 mg/L to 4950 mg/L for STP sludge. The COD values ranged from 2600 mg/L to 3980 mg/L for ETP sludge and from 2980 mg/L to 9867 mg/L for STP sludge. The COD concentration indicates the organic content of sludge (Al Yaqout, 2003). In the ETP sludge, electrical conductivity was higher and ranged between 6830 and 16560 µS/cm. This indicates that ions are present in the sludge (Pandey *et al.*, 2011).

In our study, heavy metal concentration was also higher in ETP sludge and composed of iron, zinc, cadmium, copper, nickel, and lead in high concentration, chromium, and mercury in low concentration. Sludge characteristics from the current study were comparable to the values found in the literature (Zhan & Poon, 2015; Anwar *et al.*, 2018). Heavy metals concentration in ETP sludge varies depending on the industry, the type and amount of dye chemicals used in the process (Anwar *et al.*, 2018). The ETP sludge characterization studies conducted by Pandey *et al.*, (2011) found that the sludge was mostly composed of Zn (73.48–386.94 mg/kg), Ni (23.72–88.75 mg/kg), Pb (20.31–52.04 mg/kg), total chromium (32.00–316.33 mg/kg), Cd (4.25–5.41 mg/kg), Cu (39.81–389.83 mg/kg), Co (12.12–13.46 mg/kg), and hexavalent chromium (below detection limit).

Table 2: Characteristics of raw ETP sludge before digestion

Parameters	Units	ETP Sludge	STP Sludge
pH	-	9 ± 0.6	6.5 ± 0.20
Temperature	°C	31.9 ± 0.78	30.6 ± 2.51
Conductivity	µS/cm	4.5 ± 0.92	10.13 ± 2
TDS	Ppm	1711.5 ± 2375.17	6500 ± 1322.88
Total alkalinity	mg/L	246.4 ± 161.49	56.8 ± 4.81
Ammonia Nitrogen	mg/L	85 ± 34.03	188 ± 63.09
Chemical oxygen demand (COD)	mg/L	3386.7 ± 710.02	5655.67 ± 3691.39
Biological oxygen demand (BOD)	mg/L	1816.7 ± 838.65	2916.67 ± 1760.91
Volatile suspended solids(VS)	g/l	56.5 ± 7.75	75.5 ± 49.92
Total solids (TS)	g/l	51.5 ± 15.38	51.35 ± 4.17
Carbon-Nitrogen (C/N) ratio	-	3.7 ± 0.18	10.9 ± 0.57
Cadmium (Cd)	mg/kg	56.9 ± 7.22	42.34 ± 1.66
Chromium (Cr)	mg/kg	4.15 ± 0.30	21.31 ± 0.71
Copper (Cu)	mg/kg	42.16 ± 2.52	16.78 ± 0.53
Lead (Pb)	mg/kg	31.59 ± 10.92	9.32 ± 0.29
Nickel (Ni)	mg/kg	48.43 ± 2.52	5.35 ± 0.94
Zinc (Zn)	mg/kg	111.42 ± 7.79	77.93 ± 2.29
Iron (Fe)	mg/kg	434.31 ± 590.49	24.17 ± 2.33
Mercury (Hg)	mg/kg	0.68 ± 0.12	0.04 0.02

4.2 Mixed Sludge Characteristics

Characteristics of the mixed sludge (ETP sludge: STP Sludge) are shown in Table 3. The pH values ranged from 6.68 to 9.49. VS were higher in raw STP sludge than in raw ETP sludge.

Moreover, results showed that VS of the different sludge mixtures were slightly similar to one of the raw ETP sludge and the values ranged from 38.6 to 110.8. VS are indicators of the degradability potential of sludge (Fu *et al.*, 2012).

Table 3: Characteristics of the mixture at different ratios

Parameters	Units	Characteristics of the mixture at different ratios (ETP sludge: STP Sludge)				
		4:0	3:1	1:1	1:3	0:4
pH	-	9.49	9.48	9.27	7.84	6.68
TS	g/L	68.6	90.6	60	100	48.4
VS	g/L	47.8	40	62.2	38.6	110.8
COD	mg/L	2600	1800	2800	2300	2400
BOD	mg/L	850	900	750	1100	1350
MC*	%	93.1	89.9	93.3	88.9	94.6

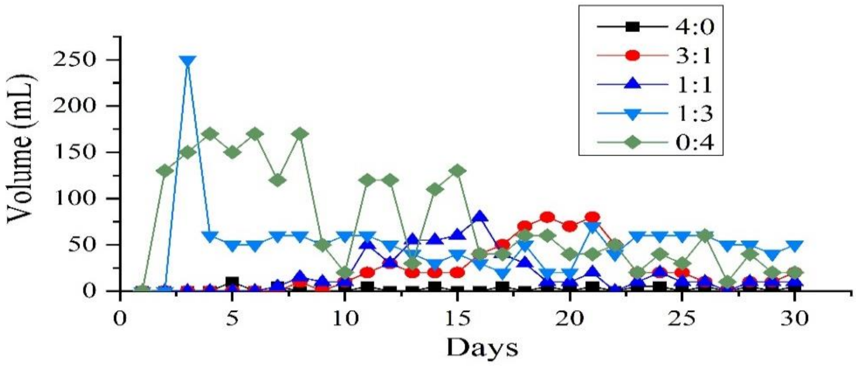
4.3 Biogas Volume at Different Mixing Ratios

During the study, biogas testing was performed in laboratory-scale reactors, and experiments were conducted for 30 days, under mesophilic (37 °C) conditions. The cumulative and day-wise biogas yield at different mixing ratios (ETP sludge: STP Sludge) are presented in Fig. 7. Zhen *et al.* (2015) reported that the mono-digestion of textile sludge is less efficient for biogas production. In the current study, the mono-digestion of ETP sludge was slow and resulted in low biogas production. The produced biogas volume was only 65 ml after 30 days of the experiment. These results confirm that ETP sludge has a poor biodegradability.

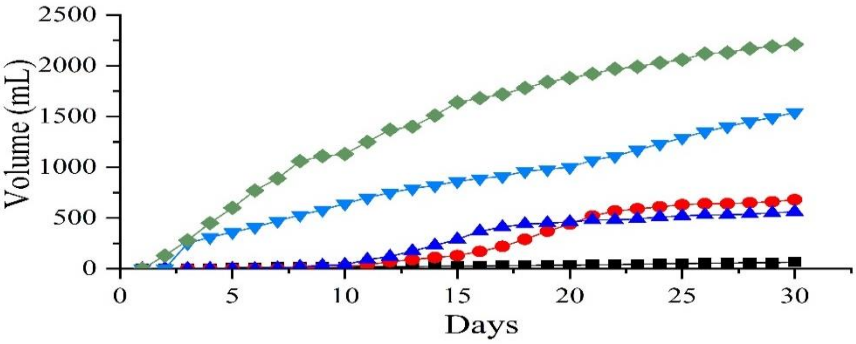
However, the addition of STP sludge to ETP sludge significantly improved the biogas volume generated and methane yield compared to the mono-digestion of ETP sludge. High biogas production was achieved at mixing ratios of 3:1, 1:1, 1:3 and the highest volume was from the ratio of 1:3. Therefore, the greater the volume of STP sludge, the greater the volume of biogas generated. Biogas yield was enhanced due to the high organic content of STP sludge.

The C/N ratio was 3.7 and 10.9 for ETP sludge and STP sludge respectively. ANOVA analysis of cumulative biogas production at different mixing ratios of ETP sludge to STP sludge showed a significant difference ($p < 0.05$). Therefore, we can conclude that the digestion of ETP sludge with STP sludge contributed to biogas yield improvement at different mixing ratios.

Guha *et al*. (2015) conducted similar experiments by co-digesting textile ETP sludge with cow dung, the results showed that 525 cc (525 mL) of biogas was obtained after 18 days, by using 1.5 kg of ETP sludge, 200 g of cow dung and 1 L of sludge liquor. 1 g of sodium bicarbonate ($NaHCO_3$) was added to maintain the pH to 8.5. In another experiment, 350 cc (350 mL) biogas was generated after 3 days, by using 500 g of ETP sludge, 50 g of cow dung, 1.5 L of sludge liquor, and 4 g of $NaHCO_3$.



(a) Day wise biogas volume



(b) Cumulative biogas volume

Figure 7: Day-wise biogas volume (a) and cumulative biogas volume (b) at different mixing ratios (ETP sludge: STP Sludge)

4.4 Methane Content at Different Mixing Ratios

The methane content of the biogas was analyzed several times for the different mixing ratios during the experiments and the results are shown in Table 4. The results revealed an upward trend in methane production, although mono-digestion of ETP sludge yielded the lowest (39.6%). In the current investigation, there was no methane production in the first stages of AD but slowly increased progressively during the process. Methane production was effective in all the mixing ratios except for ETP sludge only (1:0). Oxygen was found in the biogas composition (3.2 – 20.1%) and can be considered as one of the factors affecting biogas yield.

Babel *et al*. (2009) have reported that high oxygen and heavy metals concentration affect the methanogenesis step during the AD process. Methane production was similar from co-digestion of ETP sludge and STP Sludge at ratios of 3:1, 1:1, 1:3, and the highest yields were respectively 87.9%, 68.9%, and 69.5% of the gas composition. The addition of STP sludge positively affected methane yield.

Variation in methane yield can be justified by the addition of biodegradable fraction from the co-substrate organic matter (STP sludge). Moreover, increased methane yield can be associated with the improvement of the C/N ratio (Grosser *et al*., 2017).

The methane yield observed during our study is comparable to the findings from the work of Kumar *et al*. (2020). In their lab-scale study, the authors have tested methane production from textile sludge, co-digested with cow dung (CD) in 1:1 ratio under controlled conditions (36 ± 1 °C; 30-day HRT). They have found that methane yield with CD, as co-substrates was 244.1 mL/g VS added, while mono-digestion of textile sludge did not produce any biogas

Table 4: Methane content of biogas at different mixing ratios

Day	Cumulative methane content (%)				
	4:0	3:1	1:1	1:3	0:4
1	0	0	0	0	0
5	3.8	3.5	3.3	3.7	3.1
10	39.6	42.8	44.3	40	53.9
15	15.8	51.7	64.7	69	65.06
20	7	87.9	68.9	69.5	59
25	1.3	25.7	59.1	63.4	61.9
30	3.6	49.5	59.5	63.1	66.8

4.5 Effect of Substrate Type and Thermochemical Pretreatment on Biogas Production

The effect of thermochemical pretreatment on substrate biodegradability was investigated. The mixtures were treated under high thermal temperature (170 °C) for 60 minutes, followed by the addition of 3 g/L of NaOH to the sludge mixtures to maintain the pH between 6.5 and 7.5. The goal of sludge thermal hydrolysis is to increase methane yield and improve sludge dewaterability, at the lowest HRT possible in the reactor. Stuckey and McCarty (1984) reported that thermal hydrolysis improved biodegradability (based on methane yield) of waste activated sludge (WAS). The combined effects of substrates composition and thermochemical pretreatment are shown in Fig. 8.

The first experiment comprised the co-digestion of ETP sludge and STP sludge as well as 50g of CD to increase the biodegradability of the sludge mixtures. Biogas volume from this experiment was observed to be 550 mL, 600 mL, and 1650 mL for a mixing ratio of 3:1, 1:1, and 1:3 respectively. In this experiment, the monitoring of biogas production stopped after 3 weeks due to a slow and progressive decrease in production. The decrease in biogas production did not affect the methane production although the carbon dioxide (CO2) content of the biogas was decreasing slowly.

Methane yield was efficient, and its production increased exponentially during the first 10 days of the experiments. Biogas is typically composed of methane (55 – 70 %), carbon dioxide (35 – 40 %), hydrogen sulfide (20 – 20000 ppm), and other gases such as hydrogen and ammonia, in low concentration (Vögeli *et al.*, 2014). Table 5 describes the biogas composition at different mixing ratios with different feedstocks. For ETP sludge to STP sludge at a mixing ratio of 3:1, methane gas was found to be 55.2 % of total gas composition. Furthermore, methane gas was 65.5 % and 70.8 % respectively for ETP sludge to STP sludge ratios at 1:1 and 1:3.

Similar thermal pretreatment conditions (170 °C for 30 minutes) applied on WAS, revealed that sludge biodegradability increased (in terms of mL CH_4/g VS added or methane yield), for the pretreated WAS compared to the non-pretreated WAS (Donoso-Bravo *et al.*, 2011; Pérez-Elvira *et al.*, 2008; Pérez-Elvira *et al.*, 2012). Mottet *et al.* (2009) also reported that treatment at 170 °C of poorly biodegradable WAS, showed a 78 % increase in methane yield. Methane production increased from 128 to 228 mL CH_4/g VS added.

The second experiment with sawdust (50 g) as third substrates was also conducted under the same conditions as the previous one to make a comparative assessment. Biogas was observed during the first 10 days of the experiment and the production described an upward trend. After 21 days, the total biogas volume was 680 mL, 1130 mL, and 2020 mL for ETP sludge to STP sludge mixing ratio of 3:1, 1:1, and 1:3 respectively. Biogas from ETP sludge co-digested together with ETP sludge and Sawdust provided a better biogas yield. Methane content was 54.6, 67.1, and 71.9, respectively for sludge mixtures at ratios of 3:1, 1:1, and 1:3.

We can conclude from these two experiments that the addition of a third substrate as well as thermochemical pretreatment was efficient in improving sludge biodegradability and enhanced biogas yield compared to the initial experiment. Moreover, the HRT was reduced to 21 days. However, the cumulative biogas yield from the two experiments did not vary significantly, even though they were higher than the initial experiment. The ANOVA of cumulative biogas yield at different mixing ratios of ETP sludge to STP sludge with an addition of a third substrate did not show a significant difference for the two experiments ($p > 0.05$). Therefore, the CD as well as sawdust can both be considered as good feedstock for biogas yield enhancement.

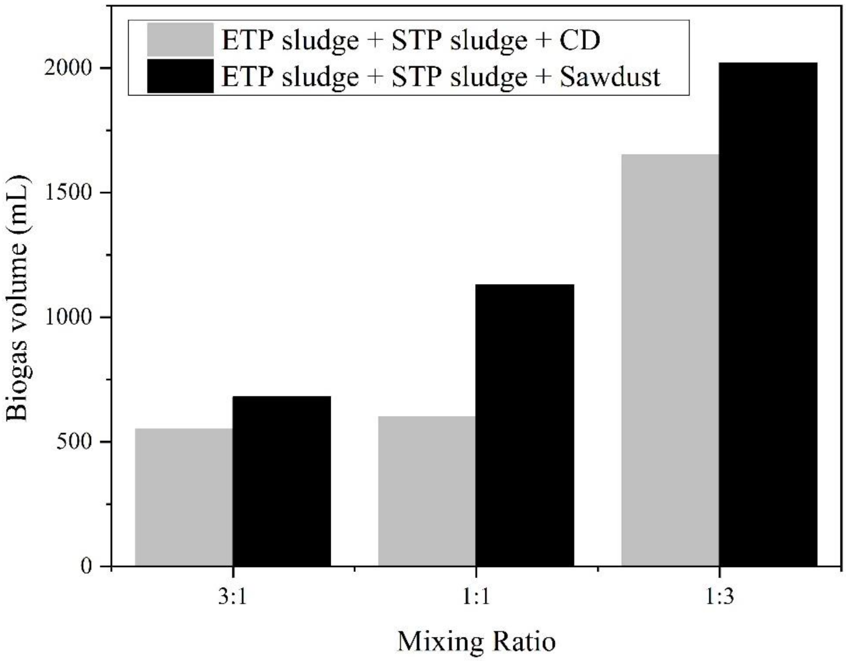


Figure 8: Comparative biogas volume for different sludge mixtures under optimized conditions

Table 5: Biogas composition at different mixing ratios with different feedstocks

Parameters	Formula	Unit	ETP sludge + STP sludge + CD			ETP sludge + STP sludge + sawdust		
			3 :1	1 :1	1 :3	3 :1	1 :1	1 :3
Biogas volume	-	mL	550	600	1650	680	1130	2020
Methane	CH_4	%	55.2	65.5	70.8	54.6	67.1	71.9
Carbone Dioxide	CO2	%	26.6	32.5	30.5	28.2	31.3	29.9
Oxygen	O2	%	8.1	8.8	3.5	8.7	5.8	5
Ammoniac	NH3	ppm	1	1	1	0	1	0
Hydrogen sulfide	H2S	ppm	188	599	255	13	19	70

4.6 Pollution Level in the Digested Sludge

Digested sludge was characterized after the biogas production to determine and assess the pollution level, but also the pollutant reduction efficiency. Selected parameters such as COD, BOD, and heavy metals were analyzed after anaerobic digestion of sludge mixtures following the standards methods and the results are shown in Table 6. In this study, VS was also found to decrease after biogas production**.** The effectiveness of the AD process relies on VS removal efficiency (Grosser *et al*., 2017)**.** The COD and BOD concentration was reduced in the digested sludge. The values ranged from 300 mg/L to 1100 mg/L and 280 mg/L to 700 mg/L respectively for COD and BOD. Previous studies found that the AD process was effective in reducing COD and BOD (Jain *et al*., 2015), as a result of the decomposition of organic matter by microorganisms (Utami *et al*., 2016).

The percentage reduction of organic and inorganic pollutants in the digested sludge is presented in Table 7. The results revealed a decrease in heavy metal concentration after biogas production, this may be due to precipitation or dilution effect. According to the initial concentration of metals presented in Table 7, only Cd, Pb, Fe, and Hg were sufficiently reduced and the percentage reduction ranged from 47.2%-74.3%, 18.1%-55.3%, 31.6%-96.1%, and 14.5%-69.7% respectively for Cd, Pb, Fe, and Hg. Heavy metals are present in sludge in many forms (Dewil *et. al*, 2007): Bound to organic matter, bound to manganese oxides and iron, bound to carbonates, and exchangeable. Soluble metals are released in an oxidizing environment, as a result of organic fraction degradation, whereas the residual fraction does not dissolve but rather keeps metals in its crystal structure. In an anoxic environment, manganese oxides and iron are thermodynamically unstable while the carbonate fraction is pH sensitive. Probably, the water ionic composition, sorption, and desorption processes affect the exchangeable fraction.

Table 6: Sludge mixtures characteristics at different mixing ratios after digestion

Parameters	Units	ETP sludge before digestion	Sludge mixtures characteristics after digestion					TBS guideline values
			4:0	3:1	1:1	1:3	0:4	
pH	-	9	9.35	8.19	8.02	7.38	6.85	6.5 – 8.5
TS	g/L	51.5	59.8	67.64	58	70.36	44.28	-
VS	g/L	56.5	25.4	35.6	30.4	34.8	31.4	-
COD	mg/L	3386.7	300	530	1100	610	310	60
BOD	mg/L	1816.7	280	350	320	530	700	30
Cadmium (Cd)	mg/kg	56.9	19.42	30.06	14.63	15.17	41.59	0.1
Chromium (Cr)	mg/kg	4.15	4	4.07	3.74	3.68	3.7	1.0
Copper (Cu)	mg/kg	42.16	34.71	36.86	34.95	38.98	41.09	2.0
Lead (Pb)	mg/kg	31.59	25.87	25.44	19.9	16.91	14.11	0.1
Nickel (Ni)	mg/kg	48.43	43.78	40.38	48	47.8	46.3	0.5
Zinc (Zn)	mg/kg	111.42	95.98	93.95	100.09	90.93	100.75	5.0
Iron (Fe)	mg/kg	434.31	297.12	191.23	150.92	23.31	17.05	5.0
Mercury (Hg)	mg/kg	0.68	0.44	0.48	0.27	0.58	0.21	0.005

Table 7: Percentage reduction of pollution level in the digested sludge at different ratios

Ratios	COD removal (%)	BOD Removal (%)	Heavy Metals reduction (%)							
			Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Nickel (Ni)	Zinc (Zn)	Iron (Fe)	Mercury (Hg)
4 :0	88.5	67.1	65.9	3.6	17.7	18.1	9.6	13.9	31.6	34.9
3 :1	33.8	61.1	47.2	1.9	12.6	19.5	16.6	15.7	56.0	30.0
1 :1	56.3	57.3	74.3	9.9	17.1	37.0	0.9	10.2	65.3	61.0
1 :3	53.1	51.8	73.3	11.3	7.5	46.5	1.3	18.4	94.6	14.5
4 :0	77.9	48.1	26.9	10.8	2.5	55.3	4.4	9.6	96.1	69.7

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study explored the potential of producing biogas from textile ETP sludge, as a waste management strategy for textile processing industries. Results revealed that the major challenge associated with biogas production using textile effluent treatment plant sludge is the instability of the initial concentration of toxic pollutants in the sludge, which may be low or high depending on the textile processing conditions. However, based on the outcome from our laboratory experiments, the co-digestion of ETP sludge with readily available substrates such as STP sludge, cow dung, or Sawdust can be an efficient way to improve biogas production. Moreover, a thermochemical treatment of the sludge before biogas testing was found to be effective in improving biogas yield as well as methane content of the gas. The pollution level in the residual sludge after biogas production was found to be lower, confirming that AD is a good technique for textile sludge treatment, and biogas production using AD is an eco-friendly means for energy recovery in textile industries.

5.2 Recommendations

(i) Considering energy consumption by the company and the quantity of sludge generated from the wastewater treatment plants, mixing of ETP sludge and STP sludge for biogas production is a sustainable sludge management alternative.

(ii) The digested sludge can be reused after biogas production as underlying material for constructing roadways. After biogas production, the pollutant concentration level is diluted, and the residual sludge is found safe for this type of reuse.

(iii) The last recommendation is set for the limitations of this study. Further research dealing with the biogas production and methane yield using larger pilot scale are highly suggested. Future research should investigate the computation of the amount biogas from STP sludge alone, and the amount of biogas from the mixture of STP sludge and ETP sludge. A study that deals on the analysis of substrate composition after biogas production is recommended, to evaluate the reuse potential of the residual sludge.

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Potential of anaerobic co-digestion in improving the environmental quality of agro-textile wastewater sludge

Jean G. Tapsoba, Hans C. Komakech and Johnson Ouma

ABSTRACT

Sludge from textile effluent treatment plants (ETP) remains a challenge for many industries due to inefficient and limited waste management strategies. This study explores the potential of using anaerobic digestion (AD) to improve the environmental quality of textile ETP sludge. The AD of ETP sludge is affected by the low C/N ratio (3.7), heavy metal content, and toxicity. To improve the process, co-digestion of ETP sludge with different substrates (sewage sludge, cow dung, and sawdust) under mesophilic conditions (37 °C), followed by a thermochemical pretreatment was assessed. The results showed that anaerobic co-digestion of the textile sludge with the co-substrates is effective in reducing pollution load. It was found that organic matters degraded during the 30-day AD process. The COD and BOD reduction was in the range of 33.1–88.5% and 48.1–67.1%, respectively. Also, heavy metal (Cadmium, Lead, Iron, and, Mercury) concentration was slightly reduced after digestion. Maximal biogas yield was achieved from co-digestion of textile sludge and sewage Sludge at a mixing ratio of 3:1, 1:1, and 1:3, and methane content was respectively 87.9%, 68.9%, and 69.5% of the gas composition. The results from this study show that co-digestion will not only reduce the environmental pollution and health risks from the textile industry but also recover useful energy.

Key words | anaerobic digestion, biogas, sludge management, textile sludge, wastewater treatment plant

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HIGHLIGHTS

- The use of anaerobic co-digestion for textile sludge treatment and energy recovery were investigated.
- Textile effluent treatment plant sludge composition and toxicity affects its biodegradability.
- The addition of co-substrates with high C/N to the textile sludge improved the biodegradability and yielded highest biogas volume.
- Anaerobic co-digestion was able to improve the environmental quality of the sludge. A decrease in COD, BOD, and heavy metals concentration was observed.

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INTRODUCTION

The management of industrial wastewater remains a major challenge in Sub-Saharan Africa. For most countries, only a small fraction of municipal wastewater is being treated through waste stabilization ponds, which comprise a series of ponds stabilizing organic matter through biological processes. However, most of these ponds are not designed to receive industrial wastewater because of their toxicity to important microorganism in the biological treatment process. As a result, most industries are required to construct their own industrial effluent treatment plants. For textile industries, this is a challenge because of the complexity of the type of wastewater they produce. The effluent characteristics of textile wastewater often vary with the production demands and type of product used. Textile processing industries often use dyes and bleaching agents which require a huge amount of freshwater resulting in the production of toxic wastewaters (Jahagirdar *et al.* 2013). There is no single treatment method capable of efficiently eliminate the pollutants in the wastewater (Lee *et al.* 2001). Generally, every treatment technique has its advantages and limitations. Various methods including filtration, coagulation, and flocculation techniques only convey organic pollutants as well as inorganic pollutants from one stage to another. However, an adequate treatment technique requires comprehensive and adapted treatment methods, as well as skilled technicians for the operation, and maintenance of the treatment system (Jegatheesan *et al.* 2016). The textile wastewater treatment, through combined traditional treatment methods such as physical, chemical, or biological are found to be suitable but very expensive and leads to the production of bio-sludge (Nguyen & Juang 2013). For instance, the use of chemical coagulation and flocculation techniques require considerable financial means due to the high cost of chemical reagents. Moreover, this technique results in the production of a high volume of sludge, causing handling and discharge issues (Pang & Abdullah 2013). In places where the local authorities' capacity to enforce environmental regulation is weak, most industries often discharge their effluent untreated into the surrounding lands and water bodies. However, due to increased public awareness on this matter, most African countries have adopted strict environmental pollution control measures and laws to prevent the discharge of untreated wastewater.

In Tanzania, many industries have installed their Effluent Treatment Plant (ETP) for treating generated wastewater prior to disposal. For textile industries, the sludge generated from the treatment process may still be toxic for direct discharge into the environment. Textile effluent sludge, a by-product of the treatment process, often contains organic and inorganic matters, including heavy metals such as Fe, Cu, Cd, Zn, Cr, etc., which are toxic to both human health and the environment. The pollutants in the sludge come from a wide range of chemicals and dyes used during textile processing (Guha *et al.* 2015). As a result, most industries would opt to store their sludge on site. Since, about 1–10 tonnes of textile sludge can be produced per day, storage will quickly become an issue (Thangavel & Rathinamoorthy 2015). This is currently the case with A–Z Textile limited in Arusha, its treatment plant is generating a huge amount of sludge daily. Landfilling, ocean disposal, incineration, and composting have been widely tested. However, these management plans have some limitations due to their adverse effects on the environment. Previous studies have reported that landfilling and incineration are not suitable for textile sludge management. Landfilling is responsible for landfill leachates, which pollute groundwater and soils. The incineration technique can also be harmful due to releases of toxic pollutants and the production of contaminated ash. Moreover, these two methods are also of high costs for construction and maintenance (Emery *et al.* 2016). Composting of textile sludge on crop plants is found to be unsafe due to toxic pollutants remaining in the sludge that may affect the human body through the food chain (Guha *et al.* 2015).

Co-digestion of substrates using Anaerobic Digestion (AD) has been suggested as a potential option for the treatment of industrial wastewater sludge (Samson 2015; Shoukat *et al.* 2019). Anaerobic digestion is widely used for sewage sludge stabilization and its advantages include the reduction of sludge volume, production of biogas, and enhancement of sludge dewaterability. Also, the process is proven to be cost-effective (Zhen *et al.* 2015). However, the AD process could be adversely affected by the toxicity of pollutants contained in the sludge.

Common techniques for improving the AD process generally include co-digestion of substrated with high C/N ratio, pretreatment, and pH variation. Hagos *et al.* (2017) have reported that cow dung (C/N ratio 16–25) and sawdust (C/N ratio 200–500), can both improve the AD process, add nutrients for microorganisms, and enhances the biogas production. A study conducted by Zhen *et al.* (2017) has revealed that optimum condition for thermal hydrolysis (TH) was a temperature of 170 °C for treatment time ranging between 30 and 60 minutes. Such a condition was found to reduce the retention time by 5 days and increase biogas production. Thermal hydrolysis is known for its advantages of odor removal, sludge quantity as well as pathogens reduction. Also, it contributes to improving sludge dewaterability. Jain *et al.* (2015) have reported that a pH between 6.5 and 7.5 is optimal for the microbial activities and enhances a better biodegradability of the substrate. However, pH values above this range are known to adversely affect the methanogens.

In this study, we assessed the performance of effluent treatment plants being used by the A-Z industry to treat its agro-textile wastewater in Arusha. Based on the performance assessment, we explore ways to co-digest the final sludge to realize waste-reduction and also improve the environmental quality of the industrial process.

Application of anaerobic digestion for industrial wastewater treatment

Several studies have explored various anaerobic digestion technologies for textile wastewater treatment and reuse. Gnanapragasam *et al.* (2011) conducted batch reactor experiments using the AD process for treating textile dye effluent to remove color and reduce COD. The setup was composed of a reactor of 5 L capacity, for the combined treatment of synthetic textile dye and starch wastewater at different mixing ratios of 20:80, 30:70, 40:60, 50:50 and 60:40. They reported that the optimum ratio was 30:70 and the percentage reduction of COD and color were respectively 81.0% and 87.3%. The authors concluded that the results from the batch studies can be used to design a large-scale continuous reactor for the treatment of combined textile dye and starch wastewater under the same conditions.

Punzi *et al.* (2015) used a setup composed of an anaerobic biofilm reactor followed by ozone treatment and revealed that the anaerobic treatment was able to achieve removal efficiency of 70% for COD (Hydraulic Retention Time was 3 days for AD). Treating the effluent using the ozonation method for 6 min was able to further reduce organic matter in the effluents. Toxicity was also found to be 20 times lower than that of the initial level. Moreover, aromatic matters of effluent were reported to be degraded by ozone. It was recommended to use the ozonation method as a post-treatment system after anaerobic digestion as it enhances the reduction of refractory compounds and toxicity.

Lin *et al.* (2017) investigated the performance of combining granular activated carbon (GAC) adsorption, AD under mesophilic conditions, and microalgae scenedesmus species cultivation. Experiments were conducted using laboratory-scale reactors for textile wastewater treatment as well as regenerating algae biomass and biogas. The wastewater was pre-treated using the GAC to limit AD process inhibition and the microalgae was used to further treat digester effluent. The combined system was able to produce methane, total hydrogen, and ethanol energy at a rate of 16.9 kJ/(L·d). Also, high pollutants removal efficiencies were obtained for chemical oxygen demand (COD) 89.5%, color 92.4%, organic acids 94.7%, and carbohydrates 97.4%. However, the authors have found that reducing COD, VFAs use, and color removal efficiencies depend on the effluent initial concentrations. Thus, for the treatment of textile dye effluent, a flow rate of 1,000 m^3/d is recommended by the authors as a conceptual treatment process. Methane production as well as biomass is predicted to be 2.07×10^7 kJ/d and 9,800 kg/7 d (7 days), respectively.

The major challenge associated with the anaerobic treatment of textile wastewaters is its toxicity to essential microorganisms. Anaerobic digestion is suitable for textile wastewater treatment but the inhibitory compounds existing in the wastewater and the sludge may lead to failure of the AD process (Kumar & Mudhoo 2013). However, the presence of heavy metals in textile wastewater and sludge has been found to have an antagonistic effect on the overall process of AD (Abdel-shafy & Mansour 2014). Heavy metals removal appears to be necessary for a good performance of the AD process. To efficiently remove metals, it is essential to know metal distribution in sludge. This useful information for removing metals is provided by sequential chemical extraction (SCE), which is widely used to describe the chemical distribution of metals in sludge. The SCE process aimed at fractionating metals in the sludge sample by using chemical extracting agents. Information about metals forms in sludge samples allows the use of a suitable method for metal removal generally by solubilization. This method mainly consists of separating the solid phase from the liquid phase, followed by precipitation from the liquid phase (Marchioretto 2003; Du 2015).

Although trace elements such as iron, manganese, and molybdenum are important for the anaerobic digestion process, some metals such as antimony, lead, mercury, arsenic, and uranium are very toxics and their biological role is very limited (Kumar & Mudhoo 2013). Various methods are widely applied to improve and avoid failure of the microbial activities during AD treatment textile wastewater. Studies have reported that co-digestion with substrates rich in carbohydrates can enhance biogas yield compared to mono-digestion of single substrates (Kumar *et al.* 2020). Also, substrates decomposition can be improved trough pretreatment methods such as thermal, chemical, enzymatic, and mechanical (Zhang *et al.* 2017; Bharathiraja *et al.* 2018). Overall, pollution level reduction in the AD is dependent on the retention time, as the degradation of the organic load is effective for longer retention time in the digester (Vögeli *et al.* 2014).

Extensive research on the application of AD for industrial wastewater treatment outcomes has been proven satisfactory. However, the secondary pollutant (sludge) from this treatment process remains a concern for textile wastewater post-treatment. There is a lack of systematic studies on textile sludge treatment, especially the application of AD technology. This study was oriented towards the application of AD on textile sludge. Additionally, the process was optimized through co-digestion with substrates such as sewage sludge, sawdust, and cow dung (CD) followed by a thermochemical treatment of the mixtures. The developed treatment scheme was tested in the laboratory.

MATERIALS AND METHODS

Case study textile effluent treatment plant

The study was conducted at the A to Z Textile Mills Ltd in Arusha, Tanzania. The company has installed its effluent treatment plant (ETP) where wastewater from the factory undergoes a traditional treatment process (pre-treatment, primary treatment, secondary and tertiary treatment) (Figure 1). The characteristics of the raw effluent from the ETP was determined as reported in Table 1. Moreover, various textile effluent characteristics were collected from the literature to compare the typical composition of the raw effluents.

The system is composed of an equalization tank, a biological tank, regulation tanks, secondary tanks, a pressure sand filter, and a final discharge tank:

1) Equalization tank: wastewater from the textile dying process is collected in the equalization tank. A blower is used at this step of the treatment process to inject air in the tank. The addition of air enhances the aeration and complete mixing of the influent wastewater. The pH is checked every 2 hours and it is maintained between 7.5 and 8 using hydrochloride acid (3.01). A pH lower than 6.5 will forbid the sludge from settling. In extreme cases, Caustic is added to maintain the pH.
2) Biological Tank: the biological treatment of the wastewater is performed under aerobic conditions. The tank is also aerated and mixed using a blower. Color removal is done using Microplus, which is a color removal coagulant (50 g/1,000 L if the color is light and 100 g/1,000 L if the color is dark). For microorganism enhancement, cow dung, urea, and fertilizer such as Diammonium Phosphate (DAP) are used.

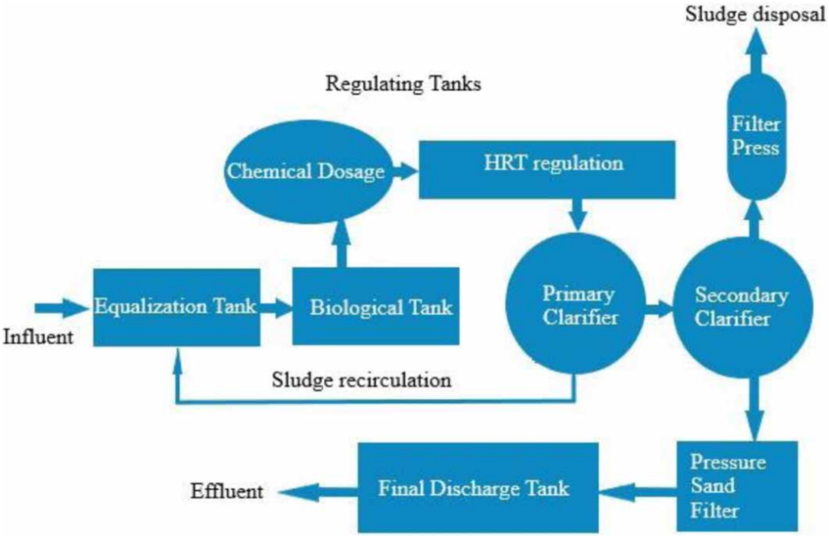


Figure 1 | Flow diagram of textile Effluent Treatment Plant (ETP).

Table 1 | Characteristics of A-Z textile wastewater and typical values

Parameter	**Unit**	**This study**	**Pakistan, Hussain *et al.* (2019)**	**Peru, Roque *et al.* (2018)**	**India, Patel & Vashi (2015)**	**Italy, Lotito *et al.* (2012)**	**China Somasiri *et al.* (2008)**
pH	–	9.49 ± 0.4	7.5 ± 0.58	8 ± 0.2	9.5 ± 0.6	8.2 ± 0.1	9.2 ± 0.2
Temperature	°C	49 ± 5.09	38 ± 3.5		25 ± 4		
Conductivity	mS/cm	8.25 ± 2.60	5.2 ± 0.63	4.056 ± 0.003	4.01 ± 0.32		
TDS	ppm	912.67 ± 55.18	3,367 ± 470		5,116 ± 358		
COD	mg/L	1,231 ± 43.84	689 ± 48	2,210 ± 3.21	760 ± 102	699 ± 236	832 ± 52
BOD	mg/L	565 ± 21.21	248 ± 31	1,162.9 ± 4.4	215 ± 50		
Cadmium (Cd)	mg/L	6.67 ± 0.89	1.05 ± 0.14	0.0007 ± 0.0			<1
Chromium (Cr)	mg/L	12.78 ± 0.02	0.19 +0.03				<1
Copper (Cu)	mg/L	36.29 ± 0.19					
Lead (Pb)	mg/L	9.58 ± 0.18		0.04 ± 0.0			
Nickel (Ni)	mg/L	39.88 ± 0.69	1.03 ± 0.05	0.002 ± 0.0			<1
Zinc (Zn)	mg/L	45.26 ± 16.93		0.0031 ± 0.0			
Iron (Fe)	mg/L	128.60 ± 156.68	2.35 ± 1.1	0.016 ± 0.0			18.04 ± 1.3
Mercury	mg/L	0.27 ± 0.33					

3) Regulation tanks: It is composed of a chemical dosage tank and Hydraulic Retention Time (HRT) regulating tank. Hydrated lime is dosed at this step to enhance the reduction of oxidizable organic pollutants but also for clarification purposes through coagulation and flocculation of particles.
4) The secondary tanks: it comprises the primary clarifier and the secondary clarifier. In the secondary clarifier, coagulation and flocculation method is used to enhance decolorization. However, this method has some limitations due to low decolorisation efficiency, but also the production of bio-sludge (Holkar *et al.* 2016). Further color removal is also performed, using Microplus dosed at around 10 g/1,000 L for light shade and 20–25 g/1,000 L for a dark shade. Along with this, a polyelectrolyte solution Animole 2030 is dosed at around 2 g/1,000 L in the Flocculator Tank, to help in particle bridging and compaction of the sludge. An electrical coagulation (EC) machine is used to generate heat that will enhance the color removal from the water. A polymer is also dosed to enhance the flotation of the sludge. The produced sludge from the secondary clarifier is transferred to the Filter Press for dewatering purposes and discharge.
5) Pressure sand filter (PSF): the effluent is directed to the pressure sand filter for final treatment, then conveyed in the final discharge tank for reuse.

Approximately 23,400 m^3 of effluent is being treated daily. One of the major challenges with the current treatment process is the large quantity of sludge produced, which is being dried and stored in bags onsite. Due to its pollution risks, A-Z currently does not have a suitable solution for the disposal of the sludge.

The company has also installed a sewage treatment plant (STP) (Figure 2), for the treatment of wastewaters generated by the households (approximately 8,000 inhabitants) located within the company. The wastewaters are coming from flushing the toilets, bathing, washing sinks, etc.

The STP is composed by the sewage collection tank, the biological tank, the clarifier, the filtering tanks, and the final discharge tank:

1) The sewage collection tank: the raw water is collected in this tank as a first step of the treatment process. A mechanical screen for heavy particles and plastics removal is installed in the collection tank and is cleaned regularly.
2) The biological tank: blowers are installed in this tank to generate air for aeration. Microplus is dosed at around 30 grams/1,000 liters. In this tank, microorganisms are grown to enhance the biological process. Therefore, cow dung and urea are added (molasses bacteria), to enhance the bacteria's growth, therefore increase the consumption of organic matter.
3) The clarifier: the wastewater clarification process is operated in this tank. Dosing of Aluminium sulfate is done in this step at 25–30 grams/1,000 liters continuously as per the flow. The addition of Aluminium sulfate allows the coagulation and flocculation process and enhances the

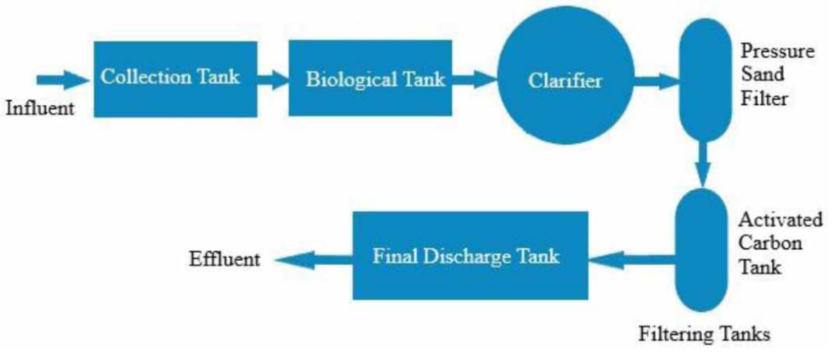


Figure 2 | Flow diagram of the Sewage Treatment Plant (STP).

treatment to reduce suspended solids and organic loads from primary clarifiers.

4) The filtering tanks: the system is composed of one Activated Carbon tank and one Pressure Sand Filter tank for clarified water filtration. The objective is to remove the small particles remaining in the clarified water. A maximum of 1 gram/1,000 liters of Sodium Hypochlorite is dosed after the filtration for smell removal. The effluent is transferred to the final discharge tank for reuse purposes.

During this study, sludge and water samples were collected at different stages of the treatment units. Wet sludge and dewatered sludge were collected respectively from the final discharge tank and the filter press (Figure 1). The sewage sludge was collected at the same site, from the STP. The sludge was packed and stored in polyethylene bags for various laboratory analyses. Water samples were collected in polyethylene plastic bottles from the inlet and outlet of the treatment plant.

Characterization of the textile industry wastewaters

Wastewater and sludge samples physical parameters, namely pH, temperature, total dissolved solids (TDS), and electrical conductivity (EC) were measured onsite and in the laboratory, using HANNA Instruments Multiparameter (RI, U.S.A.). Selected physicochemical parameters were also measured, according to Standard Methods. Method 5220D for Chemical Oxygen Demand (COD), Method 2540G for total solids (TS) and volatile solids (VS), dried at 105 and 505 °C respectively for TS and VS (APHA 1999). For Biological Oxygen Demand (BOD), samples were incubated for 5 days at 20 °C in the Incubator (model OxiTop Box), and C/N ratio was determined using the Thermo Scientific FLASH 2000 HT Elemental Analyzer. Selected heavy metals such as Cadmium (Cd), Lead (Pb), Zinc (Zn), Copper (Cu), Chromium (Cr), Nickel (Ni), Iron (Fe), and Mercury (Hg) were analyzed using an Atomic Absorption Spectrophotometer (model WFX-210). Volatile fatty acids were determined using a Gas Chromatographic method. Pollutants removal efficiency for each sample was determined using the following formula (Equation (1)):

$$\frac{C_i - C_f}{C_i} \times 100 \qquad (1)$$

where C_i and C_f represent is the initial and final concentration of pollutants in the samples respectively.

Design of laboratory-scale batch reactor

Laboratory-scale biogas batch reactor (Figure 3(c)) was assembled and used to perform experiments under mesophilic conditions (37 °C). Temperature control was done using the Memmert Water Bath method (type ONE 7). The reactor was constructed using an Erlenmeyer flask bottle (0.5 L), connected to a measuring cylinder (1 L). A plastic pipe was used to connect the reactor to the gas collector and Parafilm was used to seal the Erlenmeyer flask's outlet to prevent gas leakages. The water displacement method was used to test the biogas production. The Hydraulic Retention Time (HRT) was chosen to be 30 days and the series of experiments lasted for 122 days. Biogas volume was monitored daily and a biogas analyzer (model Biogas 5000, UK) was used to determine the methane content of the gas.

Figure 3 | Photographs of sludge sampling points (a & b) and lab-scale biogas reactor (c).

Co-digestion of ETP sludge and STP sludge

To realize waste-reduction and improve the environmental quality of the industrial process, a series of co-digestion experiments were conducted, using the textile effluent sludge and/or wastewater, as a strategy for textile waste management. Co-digestion is known for improving biochemical conditions, therefore increasing the biogas yield (Wang *et al.* 2014). Selected parameters, including pH, TS, VS, COD, and BOD were analyzed for the different mixtures. In the first experimental setup, sewage sludge was selected as the main substrate to increase the organic content of ETP sludge, but also due to its availability. Karlsson *et al.* (2014) have reported that sewage sludge is a good base that can enable better nutrient and trace element balances. ETP sludge and STP sludge were mixed at different ratios 4:0, 3:1, 1:1, 1:3, 0:4 by volume, and 100 mL of raw water was added to sludge mixtures to have a total working volume of 500 mL.

Pre-treatment conditions

The second experimental setup explored various ways of optimizing biogas and methane production. Parameters such as pH, substrate type, alkali, and thermal pre-treatment were selected for the optimization. Thus, two series of experiments were set as follow:

1) ETP sludge + STP sludge at different mixing ratios (3:1, 1:1, and 1:3) + 50 g of cow dung (CD),
2) ETP sludge + STP sludge at different mixing ratios (3:1, 1:1, and 1:3) + 50 g sawdust.

Thermal hydrolysis conditions depend on the treatment temperature and time. In the current study, high thermal hydrolysis of 170 °C was used for about 60 minutes. A 1 L beaker and a hot plate were used for the heating process. The beaker was covered with aluminum paper to avoid water evaporation. The alkali treatment consisted of adding 3 g/L of NaOH to the sludge mixtures to maintain the pH between 6.5 and 7.5. The pretreated sludge was then used in the batch digestion described above. Nitrogen gas was flushed into the reactors to ensure better anaerobic conditions of the digesters.

Statistical analysis

One-way analysis of variance (ANOVA) in Excel software was used to compare the differences in biogas yield among data obtained from anaerobic co-digestion of ETP sludge with different substrates at different mixing ratios. Statistical significance was set at a p-value <0.05. All the graphs were plotted in Origin software version 9.5.

RESULTS AND DISCUSSION

Textile ETP process performance assessment

The A to Z Textile Mills Ltd ETP performance was evaluated and the percentage reduction of each parameter is presented in Table 2. The removal efficiency of organic matters such as BOD and COD was 26.74% and 8.18% respectively. Measured BOD concentration was 550 mg/l, 510 mg/l, and 505 mg/l at the inlet, biological tank, and the outlet respectively. The COD concentrations were 1,262 mg/l, 1,010 mg/l, and 924.5 mg/l respectively at the inlet, biological tank, and the outlet. For both COD and BOD, the concentrations were above the Tanzanian Bureau of Standards (TBS) recommendation values for effluent discharge (60 mg/l for COD and 30 mg/l for BOD). Metal concentration was found high in the inlet of the ETP and slightly decreased after treatment for Chromium, Copper, Nickel, Zinc, and Iron. All the concentrations

Table 2 | Textile wastewater quality parameters before and after treatment process

Parameters	Units	ETP inlet	Biological Tank	ETP outlet	% reduction	TBS guideline values[a]
pH	–	9.77	8.87	8.16	16.48	6.5–8.5
Temperature	°C	45.40	39.45	30.72	32.33	20–35
Conductivity	mS/cm	2.3	2.1	2.03	13.3	–
TDS	ppm	976	887	873	11.80	–
COD	mg/L	1,262.00	1,010	924.50	26.74	60
BOD	mg/L	550.00	510	505	8.18	30
Cadmium (Cd)	mg/L	6.04	6.06	5.64	6.62	0.1
Chromium (Cr)	mg/L	12.77	11.25	10.95	14.25	1.0
Copper (Cu)	mg/L	36.16	36.09	36.08	0.22	2.0
Lead (Pb)	mg/L	9.71	9.66	9.43	2.88	0.1
Nickel (Ni)	mg/L	39.39	39.45	38.93	1.17	0.5
Zinc (Zn)	mg/L	33.29	36.73	14.64	56.02	5.0
Iron (Fe)	mg/L	239.39	199.99	116.76	51.23	5.0
Mercury (Hg)	mg/L	0.50	0.22	0.14	72.00	0.005

[a] Tanzania Bureau of Standards (2009).

were also above the TBS guideline values ranging between 0.005 to 5 mg/L.

ETP sludge and STP sludge characteristics

The results of ETP sludge and STP sludge characterization are shown in Table 3. The ETP sludge is found to be slightly alkaline with pH values between 8.4 and 9.6. The VS and TS were respectively 56.5 and 51.5 g/L. In the STP sludge, VS and TS were respectively 75.5 g/L and 51.35 g/L. The C/N ratio was found to be higher in STP sludge (10.46–11.27) than in ETP (3.55 to 3.81) and it could balance the C/N ratio of the sludge mixture. BOD values ranged from 850 mg/L to 2,250 mg/L for ETP sludge and from 1,900 mg/L to 4,950 mg/L for STP sludge. COD values ranged from 2,600 mg/L to 3,980 mg/L for ETP sludge and from 2,980 mg/L to 9,867 mg/L for STP sludge. In the ETP sludge, electrical conductivity was higher and ranged between 6,830 and 16,560 μS/cm. This indicates that ions are present in the sludge (Pandey *et al.* 2011). The current studies revealed that heavy metals were present in considerable quantity in both ETP and STP sludge. However, metal concentration was higher in ETP sludge and is composed of iron, zinc, cadmium, copper, nickel, and lead in high concentration, chromium, and mercury in low concentration. ETP sludge characteristics from the current study were comparable to the values found in the literature (Zhan & Poon 2015; Anwar *et al.* 2018). The effluent treatment plant sludge characterization studies conducted by Yakushev *et al.* (2013) found that the sludge was mostly composed of Cu (39.81–389.83 mg/kg), Ni (23.72–88.75 mg/kg), Cd (4.25–5.41 mg/kg), total chromium (32.00–316.33 mg/kg), hexavalent chromium (below detection limit), Pb (20.31–52.04 mg/kg), Co (12.12–13.46 mg/kg), and Zn (73.48–386.94 mg/kg).

Source of heavy metals in STP sludge are mainly coming from industrial contributions, which represent approximately 50% of the metals load of the sludge. Heavy metals in sewage sludge can emanate from the use of detergents containing trace metals such as Cd, Cu, and Zn and leachates from plumbing materials (Dewil *et al.* 2007).

Several studies have reported that heavy metals from influent are concentrated in the bio-sludge produced during wastewater treatment (Van de Velden *et al.* 2008). Heavy metals removal from wastewater is performed using chemical precipitation followed by coagulation. This process leads to the accumulation of a huge volume of sludge containing a considerable amount of heavy metals. Usually, heavy metals are adsorbed onto sludge flocs through the rapid ion-exchange process. Biopolymers are present in significant concentration in sludge flocs and play a key role of exchangers leading to the formation of anionic and cationic binding surfaces (Dewil *et al.* 2007; Ahmed & Ahmaruzzaman 2016).

Mixed sludge characteristics

Characteristics of the mixed sludge (ETP sludge: STP Sludge) are shown in Table 4. The pH values ranged from 6.68 to 9.49. VS were higher in raw STP sludge than in raw ETP sludge.

Table 3 | Characteristics of raw ETP sludge and STP sludge before digestion

Parameters	Units	ETP Sludge	STP Sludge
pH	–	9 ± 0.6	6.5 ± 0.20
Temperature	°C	31.9 ± 0.78	30.6 ± 2.51
Conductivity	μS/cm	4.5 ± 0.92	10.13 ± 2
TDS	ppm	1,711.5 ± 2,375.17	6,500 ± 1,322.88
Total alkalinity	mg/L	246.4 ± 161.49	56.8 ± 4.81
Ammonia Nitrogen	mg/L	85 ± 34.03	188 ± 63.09
COD	mg/L	3,386.7 ± 710.02	5,655.67 ± 3,691.39
BOD	mg/L	1,816.7 ± 838.65	2,916.67 ± 1,760.91
VS	g/l	56.5 ± 7.75	75.5 ± 49.92
TS	g/l	51.5 ± 15.38	51.35 ± 4.17
C/N	–	3.7 ± 0.18	10.9 ± 0.57
Cadmium (Cd)	mg/kg	56.9 ± 7.22	42.34 ± 1.66
Chromium (Cr)	mg/kg	4.15 ± 0.30	21.31 ± 0.71
Copper (Cu)	mg/kg	42.16 ± 2.52	16.78 ± 0.53
Lead (Pb)	mg/kg	31.59 ± 10.92	9.32 ± 0.29
Nickel (Ni)	mg/kg	48.43 ± 2.52	5.35 ± 0.94
Zinc (Zn)	mg/kg	111.42 ± 7.79	77.93 ± 2.29
Iron (Fe)	mg/kg	434.31 ± 590.49	24.17 ± 2.33
Mercury (Hg)	mg/kg	0.68 ± 0.12	0.04 ± 0.02

Table 4 | Characteristics of the mixture at different ratios

		Characteristics of the mixture at different ratios (ETP sludge: STP Sludge)				
Parameters	**Units**	**4:0**	**3:1**	**1:1**	**1:3**	**0:4**
pH	–	9.49	9.48	9.27	7.84	6.68
TS	g/L	68.6	90.6	60	100	48.4
VS	g/L	47.8	40	62.2	38.6	110.8
COD	mg/L	2,600	1,800	2,800	2,300	2,400
BOD	mg/L	850	900	750	1,100	1,350
MC[a]	%	93.1	89.9	93.3	88.9	94.6

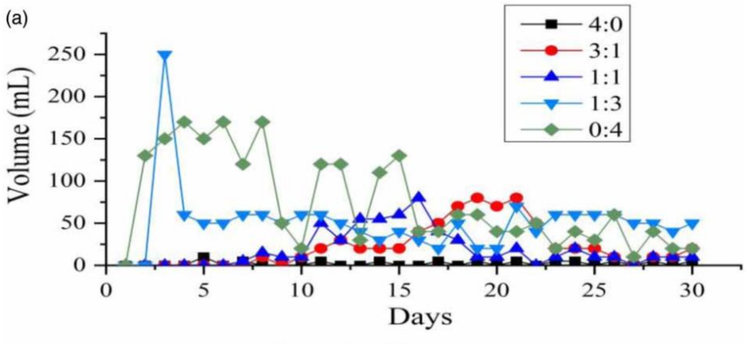
[a] Moisture Content.

Moreover, results showed that VS of the different sludge mixtures were slightly similar to one of the raw ETP sludge and the values ranged from 38.6 to 110.8. VS are indicators of the degradability potential of sludge (Bo *et al.* 2012).

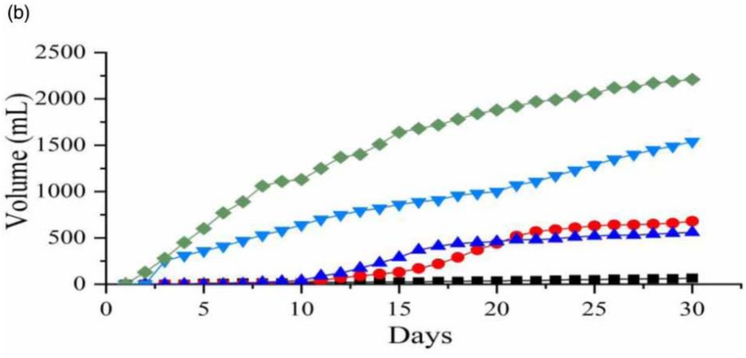
Biogas volume at different mixing ratios (ETP sludge: STP sludge)

During the study, biogas testing was performed in laboratory-scale reactors, and experiments were conducted for 30 days, under mesophilic (37 °C) conditions. The cumulative and day-wise biogas yield at different mixing ratios (ETP sludge: STP Sludge) are presented in Figure 4. Zhen *et al.* (2015) reported that the mono-digestion of textile sludge is less efficient for biogas production. In the current study, the mono-digestion of ETP sludge was slow and resulted in low biogas production. The produced biogas volume was only 65 ml after 30 days of the experiment. These results confirm that ETP sludge has a poor biodegradability.

However, the addition of STP sludge to ETP sludge significantly improved the biogas volume generated as well as the methane yield compared to the mono-digestion of ETP sludge. High biogas production was achieved at mixing ratios of 3:1, 1:1, 1:3 and the highest volume was from the ratio of 1:3. Therefore, the greater the volume of STP sludge, the greater the volume of biogas generated. Biogas yield was enhanced due to the high organic content of STP sludge. The C/N ratio was 3.7 and 10.9 for ETP sludge and STP sludge respectively. ANOVA analysis of cumulative biogas production at different mixing ratios of ETP sludge to STP sludge showed a significant difference ($p < 0.05$). Therefore, we can conclude that the digestion of ETP sludge with STP sludge contributed to biogas yield improvement at different mixing ratios.



Day wise biogas volume



Cumulative biogas volume

Figure 4 | Day-wise biogas volume (a) and cumulative biogas volume (b) at different mixing ratios (ETP sludge: STP Sludge).

Guha *et al.* (2015) conducted similar experiments by co-digesting textile ETP sludge with cow dung, the results showed that 525 cc (525 mL) of biogas was obtained after 18 days, by using 1.5 kg of ETP sludge, 200 g of cow dung and 1 L of sludge liquor. 1 g of sodium bicarbonate ($NaHCO_3$) was added to maintain the pH to 8.5. In another experiment, 350 cc (350 mL) biogas was generated after 3 days, by using 500 g of ETP sludge, 50 g of cow dung, 1.5 L of sludge liquor, and 4 g of $NaHCO_3$.

Methane content at different mixing ratios

The methane content of the biogas was analyzed several times for the different mixing ratios during the experiments and the results are shown in Table 5. The results revealed an upward trend in methane production, although mono-digestion of ETP sludge yielded the lowest (39.6%). In the current investigation, there was no methane production in the first stages of AD but slowly increased progressively during the process. Methane production was effective in all the mixing ratios except for ETP sludge only (1:0). Oxygen was found in the biogas composition (3.2–20.1%) and can be considered as one of the factors affecting biogas yield. Babel *et al.* (2009) have reported that high oxygen and heavy metals concentration affect the methanogenesis step during the AD process. Methane production was similar from co-digestion of ETP sludge and STP Sludge at ratios

Table 5 | Methane content of biogas at different mixing ratios (ETP sludge: STP sludge)

	Cumulative methane content (%)				
Day	**4:0**	**3:1**	**1:1**	**1:3**	**0:4**
1	0	0	0	0	0
5	3.8	3.5	3.3	3.7	3.1
10	39.6	42.8	44.3	40	53.9
15	15.8	51.7	64.7	69	65.06
20	7	87.9	68.9	69.5	59
25	1.3	25.7	59.1	63.4	61.9
30	3.6	49.5	59.5	63.1	66.8

of 3:1, 1:1, 1:3, and the highest yields were respectively 87.9%, 68.9%, and 69.5% of the gas composition. The addition of STP sludge had a positive effect on methane yield.

Variation in methane yield can be justified by the addition of biodegradable fraction from the co-substrate organic matter (STP sludge). Moreover, increased methane yield can be associated with the improvement of the C/N ratio (Grosser *et al.* 2017).

The methane yield observed during our study is comparable to the findings from the work of Kumar *et al.* (2020). In their lab-scale study, the authors have tested methane production from textile sludge, co-digested with cow dung (CD) in 1:1 ratio under controlled conditions (36 ± 1 °C; 30-day HRT). They have found that methane yield with CD, as co-substrates was 244.1 mL/gVS added, while mono-digestion of textile sludge did not produce any biogas.

Inhibitory effects of heavy metals on the AD process

The poor biodegradability of the ETP sludge can be explained by the sludge composition, which contains toxic heavy metals, which are likely inhibiting the AD process during the experiment. Studies have shown that a higher concentration of heavy metals in sludge samples adversely affects microbial activities (Bassan *et al.* 2016). In this study, ETP sludge was composed of Cd (56.9 mg/Kg), Cr (4.15 mg/Kg), Cu (42.16 mg/Kg), Pb (31.59 mg/Kg), Ni (448.43 mg/Kg), Zn (111.42 mg/Kg), Fe (434.31 mg/Kg), and Hg (0.68 mg/Kg). The presence of heavy metals can lead to a decrease in biogas production and an increase in intermediate organic complexes. Heavy metals also affect the AD process through physicochemical reactions. They can form compounds with intermediate AD products, precipitate with carbonate, hydroxide, and sulfide (Kumar & Mudhoo 2013; Paulo *et al.* 2015).

Effect of substrate composition and thermochemical pretreatment on biogas yield

The effect of thermochemical pretreatment on substrate biodegradability was investigated. The mixtures were treated under high thermal temperature (170 °C) for 60 minutes, followed by the addition of 3 g/L of NaOH to the sludge mixtures to maintain the pH between 6.5 and 7.5. The goal of sludge thermal hydrolysis is to increase methane yield and improve sludge dewaterability, at the lowest HRT possible in the reactor. Stuckey & McCarty (1984) reported that thermal hydrolysis improved biodegradability (based on methane yield) of waste activated sludge (WAS). The combined effects of substrates composition and thermochemical pre-treatment are shown in Figure 5.

The first experiment comprised the co-digestion of ETP sludge and STP sludge as well as 50 g of CD to increase the

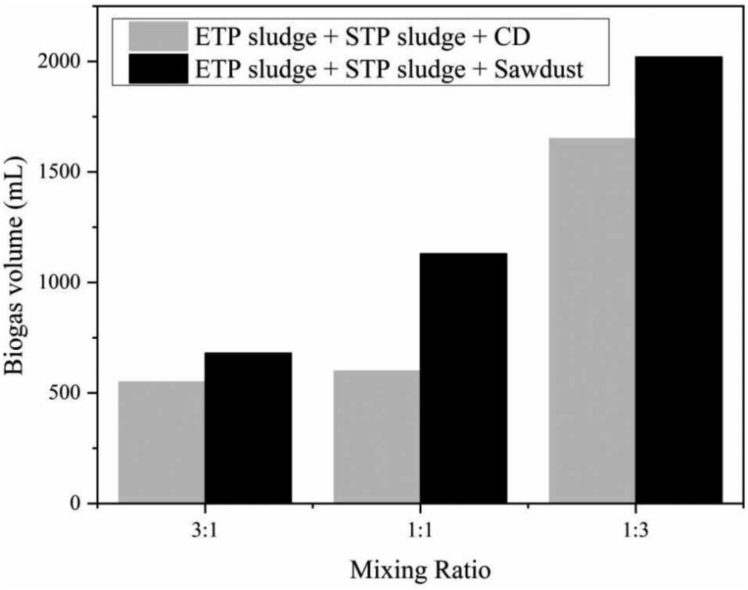


Figure 5 | Comparative biogas volume for different sludge mixtures under optimized conditions.

biodegradability of the sludge mixtures. Biogas volume from this experiment was observed to be 550 mL, 600 mL, and 1,650 mL for a mixing ratio of 3:1, 1:1, and 1:3 respectively. In this experiment, the monitoring of biogas production stopped after 3 weeks due to a slow and progressive decrease in production. The decrease in biogas production did not affect the methane production although the carbon dioxide (CO_2) content of the biogas was decreasing slowly. Methane yield was efficient, and its production increased exponentially during the first 10 days of the experiments. Biogas is typically composed of methane (55–70%), carbon dioxide (35–40%), hydrogen sulfide (20–20,000 ppm), and other gases such as hydrogen and ammonia, in low concentration (Vögeli *et al.* 2014). Table 6 describes the biogas composition at different mixing ratios with different feedstocks. For ETP sludge to STP sludge at a mixing ratio of 3:1, methane gas was found to be 55.2% of total gas composition. Furthermore, methane gas was 65.5% and 70.8% respectively for ETP sludge to STP sludge ratios at 1:1 and 1:3.

Similar thermal pretreatment conditions (170 °C for 30 minutes) applied on WAS, revealed that sludge biodegradability increased (in terms of mL CH4/g VS added or methane yield), for the pretreated WAS compared to the non-pretreated WAS (Fernández-Polanco *et al.* 2008; Donoso-Bravo *et al.* 2011; Pérez-Elvira & Fdz-Polanco 2012). Mottet *et al.* (2009) also reported that treatment at 170 °C of poorly biodegradable WAS, showed a 78% increase in methane yield. Methane production increased from 128 to 228 mL CH4/g VS added.

The second experiment with sawdust (50 g) as third substrates was also conducted under the same conditions as the previous one to make a comparative assessment. Biogas was observed during the first 10 days of the experiment and the production described an upward trend. After 21 days, the total biogas volume was 680 mL, 1,130 mL, and 2,020 mL for ETP sludge to STP sludge mixing ratio of 3:1, 1:1, and 1:3 respectively. Biogas from ETP sludge co-digested together with ETP sludge and Sawdust provided a better biogas yield. Methane content was 54.6, 67.1, and 71.9, respectively for sludge mixtures at ratios of 3:1, 1:1, and 1:3.

We can conclude from these two experiments that the addition of a third substrate as well as thermochemical pretreatment was efficient in improving sludge biodegradability and enhanced biogas yield compared to the initial experiment. Moreover, the HRT was reduced to 21 days. However, the cumulative biogas yield from the two experiments did not vary significantly, even though they were higher than the initial experiment. The ANOVA analysis of cumulative biogas production at different mixing ratios of ETP sludge to STP sludge with an addition of a third substrate did not show a significant difference for the two experiments ($p > 0.05$). Therefore, the CD as well as sawdust can both be considered as good feedstock for biogas yield enhancement.

Pollution level in the digested sludge

Digested sludges were characterized after the biogas production to determine and assess the pollution level, but also the pollutant reduction efficiency. Selected parameters such as COD, BOD, and heavy metals were analyzed after anaerobic digestion of sludge mixtures following the standards methods and the results are shown in Table 7. In this study, VS was also found to decrease after biogas production**.** The effectiveness of the AD process relies on VS removal efficiency (Grosser *et al.* 2017). The concentration of COD and BOD was reduced in the digested sludge. The values ranged from 300 mg/L to 1,100 mg/L and 280 mg/L to 700 mg/L respectively for COD and BOD**.** Previous studies found that the AD process was effective in reducing COD and BOD (Jain *et al.* 2015), as a result of organic matter decomposition by microorganisms (Isni *et al.* 2015).

Table 6 | Biogas composition at different mixing ratios with different feedstocks

			ETP sludge + STP sludge + CD			**ETP sludge + STP sludge + sawdust**		
Parameters	**Formula**	**Unit**	**3 : 1**	**1 : 1**	**1 : 3**	**3 : 1**	**1 : 1**	**1 : 3**
Biogas volume	–	mL	550	600	1,650	680	1,130	2,020
Methane	CH4	%	55.2	65.5	70.8	54.6	67.1	71.9
Carbone Dioxide	CO2	%	26.6	32.5	30.5	28.2	31.3	29.9
Oxygen	O2	%	8.1	8.8	3.5	8.7	5.8	5
Ammoniac	NH3	ppm	1	1	1	0	1	0
Hydrogen sulfide	H2S	ppm	188	599	255	13	19	70

Table 7 | Sludge mixtures characteristics at different mixing ratios after digestion

			Sludge mixtures characteristics after digestion					
Parameters	**Units**	**ETP sludge before digestion**	**4:0**	**3:1**	**1:1**	**1:3**	**0:4**	**TBS guideline values**
pH	–	9	9.35	8.19	8.02	7.38	6.85	6.5–8.5
TS	g/L	51.5	59.8	67.64	58	70.36	44.28	–
VS	g/L	56.5	25.4	35.6	30.4	34.8	31.4	–
COD	mg/L	3,386.7	300	530	1,100	610	310	60
BOD	mg/L	1,816.7	280	350	320	530	700	30
Cadmium (Cd)	mg/kg	56.9	19.42	30.06	14.63	15.17	41.59	0.1
Chromium (Cr)	mg/kg	4.15	4	4.07	3.74	3.68	3.7	1.0
Copper (Cu)	mg/kg	42.16	34.71	36.86	34.95	38.98	41.09	2.0
Lead (Pb)	mg/kg	31.59	25.87	25.44	19.9	16.91	14.11	0.1
Nickel (Ni)	mg/kg	48.43	43.78	40.38	48	47.8	46.3	0.5
Zinc (Zn)	mg/kg	111.42	95.98	93.95	100.09	90.93	100.75	5.0
Iron (Fe)	mg/kg	434.31	297.12	191.23	150.92	23.31	17.05	5.0
Mercury (Hg)	mg/kg	0.68	0.44	0.48	0.27	0.58	0.21	0.005

Figure 6 presents the percentage reduction of organic and inorganic pollutants in the digested sludge. The results revealed a decrease in heavy metal concentration after biogas production, this may be due to precipitation or dilution effect. According to the initial concentration of metals presented in Table 7, only Cd, Pb, Fe, and Hg were sufficiently reduced and the percentage reduction ranged from 47.2%–74.3%, 18.1%–55.3%, 31.6%–96.1%, and 14.5%–69.7% respectively for Cd, Pb, Fe, and Hg. Heavy metals are present in sludge in many forms (Dewil *et al.* 2007): bound to organic matter, bound to manganese oxides and iron, bound to carbonates, and exchangeable. Soluble metals are released in an oxidizing environment, as a result of organic fraction degradation, whereas the

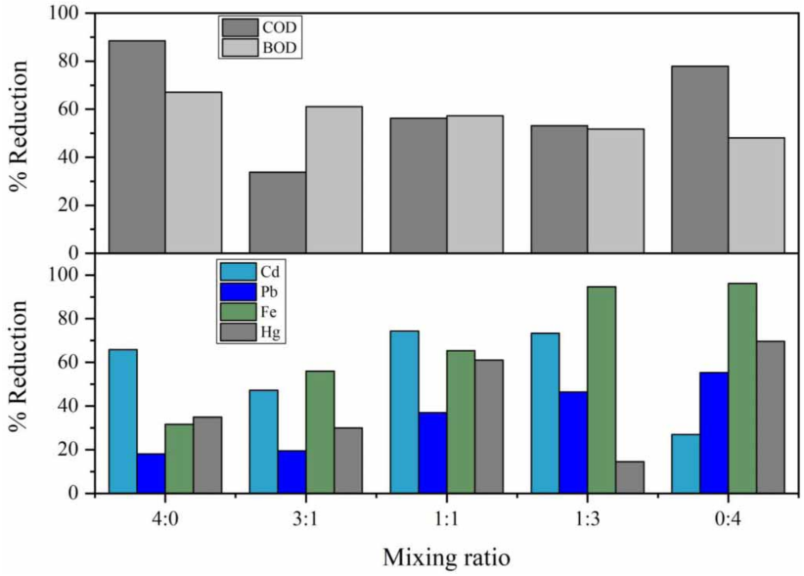


Figure 6 | Percentage reduction of pollution level in the digested sludge at different ratios.

residual fraction does not dissolve but rather keeps metals in its crystal structure. In an anoxic environment, the iron and manganese oxides are thermodynamically unstable while the carbonate fraction is pH sensitive. Probably, the water ionic composition, sorption as well as desorption processes affect the exchangeable fraction.

CONCLUSION

This study explored the potential of reducing environmental pollution from industrial wastewater sludge through biogas production. The study used effluent sludge from a large industry in Arusha Tanzania. Results show that biogas production from textile wastewater sludge is very low and likely affected by the high concentration of heavy metals found in the dye compounds used by the industry. However, biogas production can be improved through co-digestion with domestic wastewater sludge, cow dung, or sawdust. Moreover, thermochemical treatment of the sludge before digestion was found to be effective in improving biogas yield as well as methane content of the gas. The pollution level in the residual sludge after biogas production was also found to be lower, confirming that AD is likely a good technique for sludge treatment and waste management strategy for textile processing industries. It is possible to co-digest the industrial wastewater through the anaerobic digestion process, this will not only reduce the environmental pollution and health risks from the industries but also recover useful energy. We conclude from this study that the co-digestion of textile industries wastewater and/or sludge is a suitable approach for achieving waste-reduction and improving the quality of final wastewater plant effluent and sludge. Although the current study provided useful methods to enhance waste-reduction and improve environmental quality, it was limited to laboratory-scale experiments. There is a need to test the current findings using a pilot-scale and conduct long-term experiments.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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Output 2: Research Poster

Potential of anaerobic co-digestion in improving the environmental quality of agro-textile wastewater sludge

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Abstract

This study focused on improving the environmental quality of agro-textile wastewater sludge by using the anaerobic co-digestion technique for sludge treatment as well as energy recovery. After AD process, the COD and BOD reduction was in the range of 33.1-88.5 % and 48.1-67.1 %, respectively. Also, heavy metal (Cadmium, Lead, Iron, and, Mercury) concentration was slightly reduced after digestion. Maximal biogas yield was achieved from co-digestion of textile sludge and sewage Sludge at a mixing ratio of 3:1, 1:1, and 1:3, and methane content was respectively 87.9%, 68.9%, and 69.5% of the gas composition.

Findings from this study revealed the Anaerobic co-digestion of textile sludge with carbon rich substrates can be sued as an alternative option for textile sludge management.

Introduction

- Industrial (textile) wastewater management remains a challenge in many places.
- It often requires the construction of separate effluent treatment plants.
- Treatment using combination of physical, chemical or biological processes are effective but very expensive and produces toxic sludge (Nguyen & Juang, 2013; Pang & Abdullah, 2013)
- About 1 – 10 tonnes of textile sludge per day is produced (Thangavel & Rathinamoorthy, 2015).
- Anaerobic digestion is a potential treatment option for the textile sludge (Zhen et al., 2015).
- This research looked at the potential of producing biogas from agro-textile industry sludge.

Objectives of the study

The main goal of this study is to investigate the potential for improvement of biogas production as a mean of textile sludge management. The specifics objectives are:

i. To determine the physicochemical composition of the textile effluent treatment plant sludge.

ii. To evaluate the biogas production potential by co-digesting the textile sludge with substrates that are rich in organic matters.

Methodology

- Wastewater sampling and sludge collection

Sludge disposal tank

Filter Press

Biogas reactor

Figure 1: Sludge sampling points & lab-scale biogas reactor

- Laboratory analysis

Table 1: Analyzed parameters and equipment

Parameters	Equipments
pH	HANNA Instruments Multiparameter
EC	HANNA Instruments Multiparameter
Temperature	HANNA Instruments Multiparameter
Volatiles Solids & Total Solids	Oven
BOD	BOD Kit (model OxiTop Box),
COD	Spectrophotometer

Results

(b) Cumulative biogas volume

Figure 3: Day-wise biogas volume (a) and cumulative biogas volume (b) at different mixing ratios (ETP sludge: STP Sludge).

Figure 4: Percentage reduction of pollution level in the digested sludge at different ratios.

Conclusion

In conclusion, textile sludge treatment using AD process is feasible although toxics present in the sludge may have inhibitory effects on the overall performance of AD process. However, the biodegradability of the sludge can be improved trough co-digestion and various pretreatment methods. Anaerobic co-digestion in found to be an eco-friendly technique able in reducing pollutants in the residual sludge. Also this process is suitable for electricity production.

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