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# Evaluating performance of the improved hybrid passive and active mode solar dryers for processing Mangoes and Pineapples

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# EVALUATING PERFORMANCE OF THE IMPROVED HYBRID PASSIVE AND ACTIVE MODE SOLAR DRYERS FOR PROCESSING MANGOES AND PINEAPPLES

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**A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Life Sciences of the Nelson Mandela African Institution of Science and Technology**

**Arusha, Tanzania**

**July, 2021**

# ABSTRACT

Farmers in East Africa have no access to modern processing technologies because they are costly and high-energy demanding to operate. As a result, they solely rely on the traditional open sun drying (OSD) method, which is ineffective and causes further loss of the produce. In response, a modified passive-mode hybrid solar dryer dubbed 'Improved Solar Dryer (ISD)' unit was developed. A conventional active mode hybrid solar dryer nicknamed a 'Solar Photovoltaic and Electric (SPE)' dryer was fabricated. In this study, the drying performance of the individual ISD and SPE dryers was evaluated and compared against that of the OSD method. The effect of the individual ISD and SPE dryers on the nutritional content and sensory quality of the solar-dried fruits, namely mangoes and pineapples, was also assessed. The fruits were dried using the ISD and SPE dryers, and OSD methods while following randomized complete block design experimental procedures. Results show that the drying performance of the ISD and SPE dryers was better than that of the OSD method. The SPE and ISD dryers took 10 and 18 hours to effectively dry the fruit products, respectively, as opposed to the 30 hours taken by the OSD method. The mean daily ambient temperature and relative humidity were 26.8$^{o}$C and 26.7%, respectively. The mean drying air temperatures achieved by the ISD and SPE dryers were 27.7 and 40.3$^{o}$C, respectively. The mean relative humidity achieved by the ISD and SPE dryers during the entire food drying process were 25.8 and 24.6%, respectively. The mean solar thermal energy recorded for the ISD dryer, SPE dryer, and OSD method were 4795, 5994, and 3595 W/m$^{2}$ (Watts per square meter), respectively. The results suggest that the SPE dryer exhibited better drying performance than the ISD dryer. The results also confirm that the drying conditions attained by both the SPE and ISD dryers were superior to that of the OSD method. Results confirm an enhanced capacity and superior role of the ISD and SPE dryers in retaining both the sensory quality and nutritional content. Therefore, the ISD and SPE dryers are recommended for drying fruits.

# DECLARATION

I, Ssemwanga Mohammed, 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 neither been submitted nor being concurrently submitted for degree award in any other institution.

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The above declaration is confirmed.

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| **Name of supervisor 1** | **Signature** | **Date** |

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| Dr. Siraj I. Kayondo | | |
| **Name of supervisor 2** | **Signature** | **Date** |

# COPYRIGHT

# CERTIFICATION

The undersigned certify that they have read this dissertation titled “Evaluating Performance of the Improved Hybrid Passive and Active mode Solar Dryers for Processing Mangoes and Pineapples”, submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Life Sciences of the Nelson Mandela African Institution of Science and Technology.

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# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| (-/+) | Negative/ positive signs |
| 3D | 3-Dimensions |
| ACORD | Association for Co-operative Operations Research and Development |
| ANOVA | Analysis of Variance |
| AOAC | Association of Official Analytical Chemists |
| CSV | Conventional Solar Drying |
| DSD | Direct Solar Drying |
| FAO | Food and Agriculture Organization |
| ISD | Improved Solar Dryer |
| NaLIRRI | National Livestock Resources Research Institute |
| NMA-AIST | Nelson Mandela African Institution Of Science And Technology |
| OSD | Open Sun Drying |
| PDA | Produce Drying Air |
| PHL | Post-Harvest Losses |
| RCBD | Randomized Complete Block Design |
| SEC | Solar Energy Concentrator |
| SPE | Solar Photovoltaic And Electric Dryer |
| SSA | Sub-Saharan Africa |
| TPC | Total Phenolic Content |
| TPC | Total Phenolic Content |
| UV | Ultra Violet |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of the problem

The sub-Saharan Africa (SSA) region is challenged by increasing food and nutritional insecurity, and this is often caused by many factors, including low food productivity, climate change-related extremities, and financial drawbacks coupled with civil unrest, poor infrastructure, and extreme poverty (Bain & Geraldine, 2013; Clover, 2003; Fanzo, 2012; Maxwell, 1999; World Bank, 2018). Postharvest losses (PHL) of fresh produce is a silent ‘often forgotten’ factor (Hodges *et al*., 2011); and yet it is one of the leading drivers of food and nutritional insecurity in SSA (Bain *et al*., 2013; Kaminski & Christiaensen, 2014; Verpoorten & Swinnen, 2013). The PHL across SSA is estimated at 37% in cereals (Food and Agriculture Organisation [FAO], 2018) and; 40 and 50% in legumes and fruits, respectively (Affognon *et al*., 2015; World Bank, 2018). The enormous PHL is attributed to the inadequate postharvest agro-processing technologies because most farmers and agro-processors have no or very limited access to the costly modern processing technologies such as cold-chain and refrigeration, electric dryers, modified atmosphere packaging, and storage (Sagar & Kumar, 2010).

In Uganda and Tanzania, for instance, over 85% of the population directly depends on rain-fed agriculture, where the majority of subsistence horticultural farmers usually experience seasonal bumper harvests of the fresh agro-produce, especially for the highly perishable fruits (World Bank, 2018). Faced with limited access to modern processing technologies, most of the local farmers have no feasible option of prolonging the shelf life of fresh produce other than solely depending on the traditional method of drying food under the open sun. But the traditional open sun drying (OSD) method depends on the ambient weather conditions, where the quality of the dried product is often compromised by abrupt changes in humidity and erratic precipitation (Association for Co-operative Operations Research and Development [ACORD], 2014; Hii *et al*., 2012; Rembold *et al*., 2011).

Additionally, the traditional OSD method also exposes the produce to high temperatures, which further compromises the food quality (ACORD, 2014; Rembold *et al*., 2011; World Bank, 2018). Additional loss in the product quantity and quality often occurs during the OSD process through scavenging by animals and dust contamination, respectively (Kaminski &

Christiaensen, 2014; Rembold *et al.*, 2011; World Bank, 2018). And as a result, farmers in East Africa regularly experience high PHL; and is now estimated at 5-15% in cereals, 20-25% in root tubers, and over 40% in fruits (ACORD, 2014; Rembold *et al.*, 2011; Wakholi *et al.*, 2015; World Bank, 2018). Because fruits experience the highest PHLs, this study was designed to evaluate the performance of the improved passive and active mode solar dryers for processing fruits, using mangoes and pineapples as a case study.

### 1.2 Statement of the problem

The main cause of hunger and malnutrition in East Africa is the enormous PHL of perishable horticultural food produce, mainly fruits and vegetables. The high PHL is contributed by limited availability and access by farmers to the modern processing technologies, including the cold-chain and refrigeration facilities, electric dryers, and modified atmospheric storage facilities. In Tanzania and Uganda, for instance, over 90% of fruits produced are not processed due to inadequate processing industries, and the resulting PHL account for over 40% of both the nutritional and economic loss of fruits (ACORD, 2014; Kimambo, 2007; Ministry of Agriculture, Food Security and Cooperatives [MAFC], 2009).

The high PHL of fruits is one of the main causes of malnutrition in East Africa as it reduces the availability and consumption of fruits. The high PHLs of fruits have also resulted in an unpredictable seasonal availability, particularly during the prolonged dry seasons nearly after the bumper harvests. Seasonal availability of fruits emanates from the recurring failure of farmers and agro-processors to adequately process the harvested fresh perishable produce and add value to prolong shelf life for future consumption and marketing during off-seasons (ACORD, 2014; World Bank, 2018). The recent PHLs of fresh fruits in Uganda and Tanzania were estimated to be in the range of 40 to 55% and 50 to 60%, respectively (ACORD, 2014; Rembold *et al.*, 2011; Wakholi *et al.*, 2015; World Bank, 2018). Limited availability and access to modern postharvest processing technologies such as refrigeration and cold-chain facilities in East Africa are some of the primary drivers of PHLs of fresh fruits and other perishable produce (World Bank, 2018).

### 1.3 Rationale of the study

In East Africa, most subsistence farmers and agro-processors are resource-constrained and live in remote locations without electricity. This means that most of the farmers and agro-processors hardly have any access to the costly and electricity-driven modern food processing technologies such as freezing, modified atmospheric storage, refrigeration, and cold-chain facilities (Okoro & Madueme, 2004; Sagar *et al*., 2010). Therefore, the drying of food, mainly under the open sun, still remains the most viable postharvest processing technology in East Africa, as well as in other developing countries (ACORD, 2014; Okoro & Madueme, 2004; Sagar *et al*., 2010).

Despite the existence of modern drying technologies, namely: vacuum and freeze-drying, oven, microwave, and electric dryers, which operate under controlled conditions and guarantee a better quality of the dried food products (Orphanides *et al*., 2016); their use is very limited. This is so because all the aforesaid technologies are high-energy demanding and are also costly (Okoro & Madueme, 2004; Raghavan *et al*., 2005). They are, therefore, not one of the viable options for fruit processing, particularly for the resource-constrained farmers and agro-processors in Africa, particularly in Uganda and Tanzania (Chua & Chou, 2003; World Bank, 2018).

As a result, the farmers and agro-processors have no feasible alternative but to solely depend on the traditional open sun drying (OSD) method to dry their highly succulent and perishable produce, including fruits. This is because the OSD method is a cheap and sustainable option since it uses renewable solar energy in drying the produce, which is freely available in abundance (Chua & Chou, 2003; Hii *et al*., 2012; Orphanides *et al*., 2016). However, the OSD method has several major drawbacks, including contamination of food by dust and rain (Prakash *et al*., 2016; Sagar *et al*., 2010); scavenging by animals (Caparino *et al*., 2012; Lamidi *et al*., 2019); and inadequate or excessive drying (Hii *et al*., 2012; Prakash *et al*., 2016). These major drawbacks compromise the quality and quantity of the solar-dried products, where the effect is greatest in the highly succulent and perishable horticultural produce (ACORD, 2014; Prakash *et al*., 2016).

To reduce seasonality and PHL of fruits in East Africa and also address challenges associated with food, income, and nutritional security, a modified solar dryer technology was proposed as a potential alternative to the traditional OSD method. But in addition to the cost-effectiveness, renewable energy, and sustainability inclination factors, any alternative drying method should have an excellent capacity to effectively dry even the highly succulent and perishable produce, including fruits. The proposed methods should not compromise the sensory and nutritional quality of food. In this regard, ‘an improved solar dryer (or ISD dryer)’ and a Solar Photovoltaic-Electric dryer (SPE dryer) using both passive and active mode of operations were fabricated. The ISD dryer was designed to meet the drying needs of farmers at a subsistence scale, while the SPE dryer was designed for bulk processing of fresh perishable horticultural produce.

## 1.4 Objectives

### 1.4.1 General objective

The general objective of this study was to evaluate the performance of improved hybrid passive and active mode solar dryers for processing fruits.

### 1.4.2 Specific objectives

The specific objectives were:

(i) To fabricate a novel passive-mode hybrid solar dryer dubbed: ‘Improved Solar dryer (ISD)'.

(ii) To fabricate an active mode hybrid solar dryer dubbed: ‘Solar Photovoltaic and Electric (SPE)’ dryer.

(iii) To evaluate the drying performance of the individual ISD and SPE dryers.

(iv) To compare the drying performance of the individual ISD and SPE dryers with that of the traditional open sun drying (OSD) method.

(v) To assess the effect of the individual ISD and SPE dryers and OSD method on the sensory quality attributes of the dried mangoes and pineapple products.

(vi) To determine the effect of the individual ISD and SPE dryers and the OSD method on the nutritional content of the dried mangoes and pineapple products.

## 1.5 Research questions

The research questions of the study were:

(i) Is there a difference in the food drying performance of the ISD and SPE dryers due to their variations in energy sources and distinctive mode of operations?

(ii) Is there a significant variation between the drying performance of the modified ISD and SPE dryers and the traditional OSD method?

(iii) What is the effect of using the different solar drying methods, namely OSD, ISD and SPE dryers, on nutritional content, chemical composition, and sensory quality attributes of the dried mangoes and pineapples?

## 1.6 Significance of the study

East Africa countries, mainly Uganda and Tanzania, are challenged by the increasing malnutrition coupled with seasonal food shortages, including the deficit of fruits and processed fruit products, that drastically increase market prices and reduce food consumption (ACORD, 2014; Rubaihayo, 2002). In addition, ACORD (2014) further observed that most farmers in East Africa often fail to dry highly-perishable fruits during harvest resourcefully; and add-value for sell at higher market prices in the summer during scarcity, especially after bumper harvests. In Uganda and Tanzania, as in other developing countries, solar drying is the primary method of fruit processing where conventional or hybrid dryers are used (An *et al*., 2016; Nijhuis *et al.*, 1998).

Despite several modifications made in the conventional and hybrid solar drying systems, changes in the sensory quality, chemical and nutritional composition of the dried products, including loss of texture, taste, flavour, and nutrients, still happen (Babu *et al*., 2018; Mayor & Sereno, 2004). This, therefore, renders the solar drying systems ineffective for fruit processing. To address the aforesaid challenges associated with the solar drying systems, an ‘improved solar dryer (ISD)’ which exclusively combines both direct and indirect solar thermal energy was developed.

However, the ISD dryer being a passive-mode dryer, has no thermal backup, which could also limit their wide large-scale commercial use under limited solar energy, especially when drying under cloudy conditions, during rainy seasons, or when working during night shifts (Hii *et al*., 2012; Vijayan *et al*., 2016). In response, an active mode photovoltaic dryer with electric thermal backup devices hereafter called the ‘Solar Photovoltaic and Electric (SPE)’ dryer was fabricated.

In this study, therefore, the fruit drying performance of the modified ISD and SPE dryers was evaluated and compared with that of the traditional OSD method. The effect of using ISD and

SPE dryers and OSD methods on the sensory and nutritional quality of the dried products was also assessed. Evaluating the drying performance of the ISD and SPE dryers relative to that of the traditional OSD method could pave the way for the development of better performing solar drying systems. The alternative solar dryer technology could even be more efficient and effective than both the conventional solar dryers and the traditional OSD method. Likewise, assessing the effect of solar drying on the nutritional and sensory quality of the dried products could facilitate the identification of the appropriate solar drying method(s), which do not compromise both the sensory and nutritional quality of the dried products.

## 1.7 Delineation of the study

This study was quantitative in nature and focused on fabricating novel prototypes of improved passive mode hybrid solar dryer hereafter called ‘Improved Solar dryer (ISD)', and an active mode hybrid solar dryer dubbed 'Solar Photovoltaic and Electric (SPE)' dryer. The drying performance of the individual ISD and SPE dryers was evaluated and compared with that of the traditional open sun drying (OSD) method. This study also determined the effect of using the individual ISD and SPE dryers and the OSD method on the nutritional content and sensory quality attributes of the dried mangoes and pineapple products. As such, the study was limited to fabricating the novel ISD and SPE dryers and testing their drying performance and nutritional retention capacities for the dried mangoes and pineapples.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Postharvest losses of fruits

Postharvest losses (PHL) refer to measurable losses of food, including fruits, in terms of both quantity and quality during and after harvest. The PHL of fruits occurs throughout the value-chain and is caused by technical and managerial setbacks in the value-chain management process involving; harvesting, transportation, processing, storage, and marketing (FAO, 2016). Over 34.2 million tons of fruits are produced across sub-Saharan Africa (SSA) in each season (Statistical Division of the Food and Agriculture Organization [FAOSTAT], 2017). At the same time, the PHL in SSA ranges from 40 to 80% depending on the type of fruit produced, while the global PHL of fruits is estimated at 30% (Niewiara, 2016).

Kitinoja *et al*. (2015) identified sole reliance on open sun drying and other rudimentary postharvest technologies such as salting, which are ineffective and cause inadequate dehydration, physical damage, and poor temperature management, as the main cause of the enormous PHL of fruits in SSA. Hence, one of the sustainable development agenda is to reduce the PHL to 12% or lower across SSA by 2030 (Niewiara, 2016). In this study, advancing food drying technologies was identified as one of the most critical avenues for enhancing both efficiency and effectiveness of processing fruits. The advanced drying technologies could be deployed as one of the helpful strategies for reducing PHLs, especially when deployed to effectively dry the excess fresh perishable fruits, which would otherwise be lost. The dried fruit products have the opportunity for prolonged preservation and processing into value-added products.

## 2.2 The food drying technologies

Drying is the oldest technology and most common procedure used in postharvest handling and preservation of perishable horticultural produce, including fruits and vegetables (Sobukola *et al.*, 2007). The produce drying process removes biologically-active water to stable levels of moisture content, which serves to stop microbial degradation and other deteriorative biochemical reactions in the dried products (Dalgıç *et al.*, 2012). Preventing microbial degradation of the dried products serves to extend the shelf life of the dried food products (Babu *et al*., 2018; Vijayan *et al*., 2016).

The high PHL coupled with the increasing food deficits across Africa, particularly in East Africa, and other developing communities, is mainly attributed to limited availability and access to the modern, low-cost, and suitable postharvest and agro-processing technologies (Ruel *et al*., 2005). The use of the modern postharvest and food processing technologies can effectively promote the value-addition of the surplus perishable produce before being wasted, especially after bumper harvests (Ruel *et al*., 2005).

But to overcome the challenge of seasonality and also reduce the enormous PHL of fruits, both the farmers and processors employ different processing technologies such as drying, canning, freezing, modified atmospheric storage and packaging, and refrigeration and cold-chain facilities (Okoro & Madueme, 2004; Sagar *et al*., 2010). But the selection of the appropriate processing technology is dependent on the local ambient weather conditions, type of product, and socio-economic factors, including, among other factors, affordability and energy costs, ease of use, and efficiency (Okoro & Madueme, 2004; Sagar *et al*., 2010).

Comparably, the drying technology, which includes solar drying, electric dryers, oven and vacuum drying, microwave and freeze-drying methods, is so far the most popular and preferred agro-processing technology in Africa and other developing communities (Okoro & Madueme, 2004; Sagar *et al*., 2010). This is so because all the aforesaid food drying methods use relatively reduced energy and are also at a reasonably low cost compared to other non-drying technologies. This, therefore, makes the drying technology more suitable even for the resource-constrained subsistence farmers and agro-processors in SSA, East Africa, and other developing communities.

Besides, the drying process is capable of dehydrating the fresh and highly succulent produce to the desired safe storage moisture content levels, which further prolongs the shelf life of the dried products (Babu *et al*., 2018; Vijayan *et al*., 2016). The drying process also causes a considerable reduction in the weight and volume of the food products, thereby reducing packaging, transportation, and storage costs of the dried products (Chan *et al*., 2012). The drying process further retards the growth of microbes and pathogenic contamination in dried food products, including fungi and mould growth (Das & Kayang, 2008; Hii *et al*., 2012).

## 2.3 Importance of solar drying in postharvest handling of fruits and other perishable foods

Among the aforementioned food drying technologies, solar drying remains the most important and promising low-cost agro-processing technology, which can suitably reduce the high postharvest loss of fresh and perishable horticultural produce in developing communities (Sagar *et al*., 2010; Wiriya *et al*., 2009). Solar drying refers to a process of removing moisture from any fresh and succulent produce to the desired moisture content using the application of thermal radiation energy from the sun (Belessiotis & Delyannis, 2011; Visavale, 2012).

Most fresh fruits contain over 80% moisture content and are hence, classified as highly succulent and perishable (Sablani, 2006). And in the absence of modern postharvest handling and agro-processing technologies such as the modified atmospheric storage, canning, freezing, cold-chain, and refrigeration facilities; as is the case for East Africa, solar drying remains the only sure way of preserving perishable fruits and prolonging the shelf life of other dried food products (Lamidi *et al*., 2019; Ruel *et al*., 2005; Verpoorten *et al*., 2013).

The solar drying process is capable of preserving fresh perishable agro-produce, including fruits, without causing deterioration in food quality and consequently supports prolonged storage of the dried products from several months to years (Vijayan *et al*., 2016; Visavale, 2012). For instance, the solar drying process causes a significant shrinkage and loss in weight per unit volume of the solar-dried products, which considerably reduces the costly space during storage and marketing (Hii *et al*., 2012; Visavale, 2012). Transforming the bulk fresh and succulent horticultural produce, mainly fruits and vegetables, into relatively small volumes of solar-dried products serves to improve postharvest handling of the solar-dried products, mainly during transportation of the dried products to local and international markets.

The solar drying process also facilitates further agro-processing and value-addition of the dried products, such as processing of the fruit products into powder, juices, and other related fortified food products (Babu et al., 2018; Chan et al., 2012; Ruel et al., 2005; Sagar et al., 2010). Because the solar drying process involves the application of solar thermal radiation energy to vapourize moisture from the fresh succulent produce, dehydration of the product stops the growth and production of microbes, including bacteria, yeasts, and moulds which would otherwise cause food spoilage and loss (Belessiotis & Delyannis, 2011; Ruel *et al*., 2005; Sagar *et al*., 2010).

The solar drying technologies also serve to add value and prolong the shelf life of the dried products even at room temperature for consumption and marketing during the off-seasons; which is the missing link towards increasing food, income, and nutritional security in most SSA countries, particularly in East Africa (Ruel *et al*., 2005). In summary, all the uses mentioned above of solar drying are crucial in facilitating improved postharvest handling and processing of fruits and other perishable foods.

## 2.4 Types of solar drying technologies used in postharvest drying of produce

It is difficult to reliably classify the solar drying technologies because different drying methods have several distinctive technological designs and configurations as well as a blend of distinctive empirical constructions (Belessiotis & Delyannis, 2011; Krawczyk *et al*., 2012; Leon *et al*., 2002). Leon *et al*. (2002) gave an orderly comprehensive list of classification of the typical solar drying technologies based on different designs and modes of operations (or utilization of the solar energy) during the food drying process. In the aforesaid classifications, based on the mode of operation, the solar drying technology consists of two different modes of operation, namely active mode and passive modes (Ekechukwu & Norton, 1999; Hii *et al*., 2012; Leon *et al*., 2002).

The active mode food drying systems employ solar energy to warm the incoming drying air, which is circulated over or through the produce using ventilation and forced convection (Fudholi *et al*., 2010; Hii *et al*., 2012; Leon *et al*., 2002). On the contrary, the passive-mode dryers directly use the sun’s radiations to warm the produce drying air; which flows over or through the produce with and without artificial ventilation using natural air circulation and convection (Belessiotis & Delyannis, 2011; Krawczyk *et al*., 2012; Leon *et al*., 2002).

A comprehensive review and analyses of the different designs and configurations of the drying systems present four major classifications of the solar drying technologies, namely: the open sun drying (OSD) method; conventional direct and indirect solar dryers, and; hybrid (or mixed-mode) solar dryers (An *et al*., 2016; Ekechukwu & Norton, 1999; Hii *et al*., 2012; Kumar *et al*., 2016; Lamidi *et al*., 2019; Leon *et al*., 2002; Sagar *et al*., 2010). These classifications are all-inclusive, and therefore, also account for the two distinct modes of operation, thus the passive and active modes of solar drying (Ekechukwu & Norton, 1999; Hii *et al*., 2012; Leon *et al*., 2002).

### 2.4.1 Open sun drying (OSD) method

The open sun drying (OSD) method is the traditional way of drying agricultural produce under the open sun (Krawczyk *et al*., 2012). The OSD method involves putting the fresh produce under direct solar radiation until it is fully dried (Hii *et al*., 2012; Krawczyk *et al*., 2012; Kumar *et al*., 2016). The OSD is so far the most common, cheapest, and simplest method of drying food; and it is hence the most popular method of food preservation in many developing societies (Chauhan & Kumar, 2016; Chua & Chou, 2003; Hii *et al*., 2012; Krawczyk *et al*., 2012; Okoro & Madueme, 2004).

But drying of the fresh produce under the traditional OSD method fully depends on ambient weather conditions and other environmental conditions, and as such, the dried products are susceptible to contamination with moisture, dust, and animal excreta (Navale *et al*., 2015; Tiwari & Jain, 2003). The OSD drying process is often prolonged, and the dried food products do not always attain the desired safe storage moisture levels; which further compromises the quality of the dried food products (Adom *et al*., 1997; Babu *et al*., 2018).

The drying produce is also not protected from adverse weather and environmental conditions, including rainwater, wind-borne dirt, and dust and pathogen contamination, as well as scavenging by moving rodents, insects, and other pests (Folaranmi, 2008). The fresh food, including the fruits like mangoes and pineapples, when dried under the traditional OSD method, do not often attain the anticipated moisture content levels, which habitually causes undesired shrinkage and further reduces their intended shelf life (ACORD, 2014; World Bank, 2018). The food products are fully exposed to direct ultra-violet (UV) thermal radiations during the OSD drying process, which could be detrimental to both the nutritional content and quality of the dried food products (Hii *et al*., 2012; Lamidi *et al*., 2019).

Consequently, the physical, sensory, and nutritional quality of the food products dried using the traditional OSD method could be adversely affected (Hii *et al*., 2012; Lamidi *et al*., 2019). This usually causes rejection of the dried food products because they often fail to attain the minimum standards set by both the regional and international markets (Gürlek *et al*., 2009; Ivanova & Andonov, 2001).

In other words, all the aforesaid challenges experienced by the traditional OSD method limit its effective application to only cereals and legumes produce. Thus, the traditional OSD method cannot otherwise effectively dry the highly succulent and perishable horticultural products, mainly fruits. In response, direct solar-driven dryers were developed so as to address the above-mentioned food drying challenges exhibited by the traditional OSD method.

### 2.4.2 Direct solar dryers

The conventional direct solar dryer (or a cabinet dryer) is a slightly improved version of the traditional OSD method in which the fresh agro-produce is put in a cabinet to protect against contamination from dust and moisture. The cabinet is enclosed with a protective transparent glass cover (Fig. 1), where some of the solar radiation impinging on glass covers are partially reflected back to the atmosphere. In contrast, the remaining solar thermal radiations are absorbed and transmitted internally within the drying cabinet. The transmitted thermal radiation warms the produce drying air temperatures and consequently increases the internal thermal energy, which dehydrates the food produce by natural convection (Chauhan & Kumar, 2016; Hii *et al*., 2012). Figure 1 presents the drying mechanism of the fresh produce in the direct solar dryers.

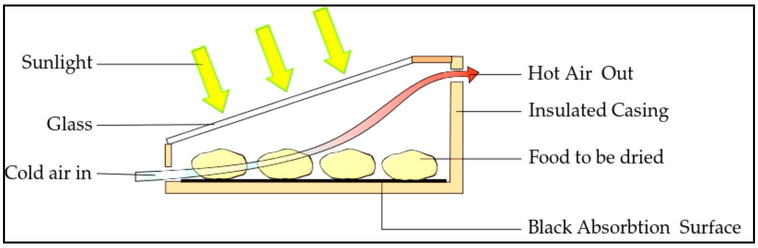

**Figure 1: Schematic representation of the mode of operation of a direct solar dryer**

The external protective glass cover also serves to reduce the direct loss of solar thermal energy from the drying cabinet, mainly through the convection process (Hii *et al*., 2012; Visavale, 2012). Using the glass cover consequently boosts the internal energy and hence improves the produce drying conditions.

Despite the aforesaid modifications made in the direct solar dryers, the food product is still vulnerable to dust contamination and longer drying durations. The food products are also fully exposed to direct ultraviolet solar radiation during the conventional solar drying process (Hii *et al*., 2012; Lamidi *et al*., 2019). To further address the above-mentioned shortcomings associated with the direct solar dryers, the conventional indirect solar-driven dryers were developed (Hii *et al*., 2012; Phadke *et al*., 2015; Sagar *et al*., 2010).

### 2.4.3 Indirect solar dryers

The conventional indirect solar dryer is a modified version of the conventional direct solar dryer, with an indirect mechanism of heat transfer and removal of redundant vapour from the drying cabinet (Hii *et al*., 2012; Visavale, 2012). The indirect solar dryer consists of two parts, namely, an opaque food drying cabinet and a solar collector (Fig. 2). The cabinet is made of several shelves with crop trays on which the fresh produce is put and dried (Belessiotis & Delyannis, 2011; Gwala & Padmavati, 2016; Phadke *et al*., 2015). The solar collector is used to trap solar energy that warms the incoming produce drying air, which drifts upwards to the food drying cabinet by natural convection (Hii *et al*., 2012; Kumar *et al*., 2016). Figure 2 presents the mode of operation of the indirect solar drying system.

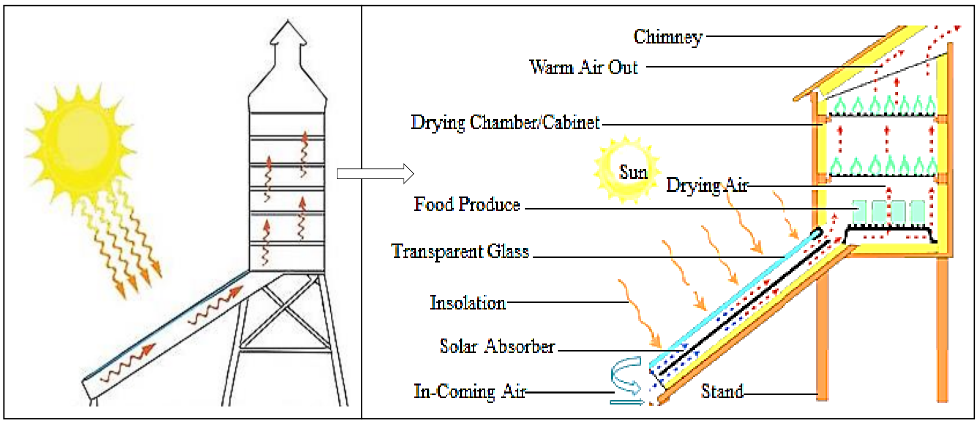

**Figure 2: Schematic representation of the mode of operation of an indirect solar dryer**

As the warmed produce drying air flows through or over the fresh produce in the food drying cabinet, it provides the thermal energy required for drying the fresh produce. The fresh produce is dried by convective heat transfer between the incoming warmed drying air and the air surrounding the fresh produce in the food drying cabinet (Fig. 2). Compared to the direct solar dryers, the indirect solar dryers are operated at higher temperatures and offer faster dehydration of the produce (Belessiotis & Delyannis, 2011; Gwala & Padmavati, 2016; Jain & Tiwari, 2015; Kumar *et al*., 2016).

However, the conventional indirect solar-driven dryers are also susceptible to the intermittence food drying process; which too inevitably compromise both the physical and nutritional quality of the dried food products (Jain & Tiwari, 2015; Lamidi *et al*., 2019; Wang *et al*., 2018; Wankhade *et al*., 2013). Confronted with the above-mentioned limitations in the convention solar drying systems; Amer *et al*. (2010), Kumar *et al*. (2016), and Raghavan *et al*. (2005) suggested that combining both the conventional indirect and direct solar-driven drying systems into a single drying system called hybrid (or mixed mode) solar dryers. Similarly, Mustayen *et al*. (2014) and Hii *et al*. (2012) also mentioned that a combination of the conventional direct and indirect solar dryers could perhaps improve the food drying performance, including drying rate, efficiency, and effectiveness.

Conversely, Lamidi *et al*. (2019) suggested that the hybrid solar-driven dryers should be made of different energy resources coupled with energy storage devices to back up the direct and indirect drying systems. Lamidi *et al*. (2019) perceived that a combination of different energy resources in the hybrid solar dryers could possibly solve the main challenge of the intermittent drying process associated with both the conventional direct and indirect solar-driven drying systems.

### 2.4.4 Hybrid solar dryers

The hybrid solar dryers simultaneously use features of both the direct and indirect solar drying systems, where their combined action produces cumulative thermal energy, which improves the food drying process (Hii *et al*., 2012; Kumar *et al*., 2016; Lamidi *et al*., 2019). In an attempt to solve the challenge of intermittent drying and improve the produce drying efficiency, several types of hybrid solar dryers with distinct system combination features have been developed and tested. The leading types of hybrid solar dryers with the successful hybrid system combination features include a solar dryer coupled with phase-change materials (Çakmak & Yıldız, 2011); a solar dryer with a phase-change thermal storage system; solar dryers coupled with biomass energy backup systems (Okoro & Madueme, 2004; Ullah *et al*., 2018); solar dryers integrated with electric heaters (Amer et al., 2010); solar dryer coupled with a latent thermal storage system (Shalaby *et al*., 2014); and a solar dryer integrated with a heat pumping system (Rad *et al*., 2013).

Despite the different modifications made in the above-mentioned hybrid solar dryers, the hybrid drying systems are still susceptible to the leading challenge of the intermittent drying process (Lamidi *et al*., 2019); and also face other drawbacks. Like in the direct and indirect solar drying systems, the hybrid dryers experience drying performance drawbacks such as prolonged drying duration, ineffective and low efficiency of drying fruits and other highly succulent and perishable produce (Nabnean *et al*., 2016; Samimi-Akhijahani & Arabhosseini, 2018). In response, this study proposed novel modifications in the existing typical hybrid solar-driven systems. And as such, a modified version of the hybrid passive-mode solar dryer hereafter called an ‘Improve Solar Dryer (ISD)’ was developed, and its drying performance was evaluated.

## 2.5 Scientific niche and relevance of the study

All the traditional solar drying methods, as well as the direct, indirect, and hybrid solar dryers, are dependent on the intensity and duration of sunshine which compromises the drying performance and quality of the dried agro-products; by prolonging drying time and causing intermittent drying, especially during the rainy, humid and cloudy weather conditions (Shalaby *et al*., 2014; Vijayan *et al*., 2016). In contrast, ineffective drying of the produce and low efficiency associated with the conventional solar drying systems is also contributed by inappropriate designs coupled with the use of poor-quality materials, especially when making the solar energy collectors (Lingayat *et al*., 2017; Nabnean *et al*., 2016). In an attempt to address these food drying challenges, Raghavan (2005) recommended integrating the direct and indirect convective solar thermal energy transfer mechanisms into a single solar dryer system. The integrated solar drying system could allow better in-flow of thermal energy and control of the drying air temperatures and; consequently improve food drying conditions, including drying efficiency (Navale *et al*., 2015; Raghavan *et al*., 2005).

It is against this background that recent efforts to improve the performance and efficiency of the conventional hybrid solar dryers have been directed towards making the following innovations: development of a hybrid solar dryer with an exclusive capacity to concentrate extra solar energy (Fleming *et al*., 2017); optimizing the design of the solar energy collector to improve its geometric and structural features (Aboghrara *et al*., 2017); integrating solar photovoltaic with an electric system (Dorouzi *et al*., 2018) and; incorporating a sun-tracking system so as to maximize the incident insolation (Samimi-Akhijahani & Arabhosseini, 2018).

Among the aforesaid novel interventions, the hybrid active mode solar dryer with an integrated solar photovoltaic and electric systems (SPE) exhibited higher drying performance, especially in terms of drying air temperatures, drying rate, effectiveness, and efficiency (Dorouzi *et al*., 2018). But Dorouzi *et al*. (2018) further observed that the initial investment costs associated with the convention active mode SPE dryer, particularly when purchasing major input materials including batteries and solar panels, as well as the energy and other operating costs, were too high relative to the convention passive-mode hybrid dryers. Therefore, the active mode hybrid SPE dryer is not a feasible option and cost-effective solution to the resource-constrained farming communities in Africa and the East Africa region in particular, despite its superior potential in improving the food drying performance.

However, all the aforementioned produce drying challenges associated with the conventional hybrid solar dryers could be solved by modifying the solar collector plate with multiple metallic solar thermal concentrators. The suggested modified solar collector plate coupled with specialized greenhouse cover materials could potentially increase the internal thermal energy and drying air temperature, thereby boosting efficiency. It is against this hypothesis that a modified version of the conventional hybrid solar dryers hereafter called an ‘Improved Solar Dryer (ISD)’ was proposed and prototyped. Before being recommended for use, the fruit drying performance of the modified ISD was assessed using pineapples and mangoes as a case study.

### 2.6 Importance of solar-dried fruits and processed fruit products

Fruits are the most important foodstuffs and form a major nutritional ingredient in processed food products (Jongen, 2002). Most fruit types, irrespective of the state (whether fresh, dried, and processed), constitute an exclusive source of critical macro and micronutrients, namely; vitamins, carbohydrates, phytochemicals, and minerals, all of which are vital to human health, growth, and development (Sablani, 2006; Sagar *et al*., 2010; Salunkhe *et al*., 1991). Nutritional studies have reported that increased consumption of tropical fruits and processed fruit products significantly reduces the incidences of chronic and other malnutrition-related diseases, including diabetes (Mayne, 1996; Mozaffarian, 2016).

A case in point is phytochemicals such as phenols which are exclusively sourced from the fruits and serve as major antioxidants in protecting humans against cytotoxicity and mutagenicity (Ouyang et al., 2018; Wu et al., 2004). The phytochemicals also constitute protective media for the regeneration of auxiliary protective dietary oxidants and pro-oxidant chelate metal ions (Garcia-Salas *et al*., 2010). Similarly, bioactive chemical compounds are essentially in the form of protein and lipids, and macro and micro mineral elements including calcium (Ca), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) are exclusively sourced from fruits or processed fruit products. The bio-active chemical content and mineral elements provide defensive effects to humans against one of the most important diseases like cancer, emphysema, arthritis, cataracts, and cardiovascular diseases (Mayne, 1996).

Therefore, deficiency of the fruit-sourced vitamins, chemicals, and mineral elements significantly contributes to impairment of human immunity and cognitive functions, causing growth failure, morbidity, and mortality (Gibson et al., 2000; Smith & Haddad, 2000). Yet in the SSA region, East African in particular, malnutrition is the leading cause of deaths of HIV-infected patients, infant morbidity, and mortality (Njeru & Mugendi, 2013; Smith & Haddad, 2000). Therefore, the consumption of fruits presents one of the most feasible and sustainable options of providing the required dietary nutrients to improve food and nutritional security in most SSA countries and East Africa (Ruel *et al*., 2005; Verpoorten *et al*., 2013).

Despite the aforesaid health and nutritional benefits, the availability of most fruit varieties in most SSA countries and East Africa, in particular, is seasonal and consumption very limited. To sustain regular consumption of the highly perishable fruits, long-term preservation to extend shelf life for availability even during the off-season is a pre-condition. And for the resource-constrained farming communities in East Africa, mainly in Tanzania and Uganda, who have very limited availability and access to the modern postharvest handling and processing facilities, solar drying remains the only feasible and sustainable method of processing and preserving food (Dehnad *et al*., 2016; Okoro & Madueme, 2004; Sagar *et al*., 2010). This is because, unlike the electric and fuel-driven drying methods, solar drying solely uses renewable solar energy, which is freely available in abundance even in remote areas (Chua & Chou, 2003; Hii *et al*., 2012; Sagar *et al*., 2010).

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Study sites and experimental design

Experiments to evaluate the drying performance of the individual ISD and SPE dryers were run simultaneously under identical weather conditions at the Nelson Mandela African Institution of Science and Technology (NM-AIST: -3.40059°N; 36.79671°E) in Tanzania. A randomized complete block design (RCBD) experimental procedure (Roger Mead, 2017) was used with three independent replicate drying cycles for each solar drying method, namely the ISD dryer, SPE dryer, and OSD method. The RCBD study design was used with mangoes and pineapples as the experimental treatments. Only optimal ripe mangoes and pineapples were collected from the same batch of the harvested lot, packed in a cool box, and transported to NM-ASIT for sample preparation and drying studies. To further ensure precision and consistency of the drying results, three independent replicate drying cycles were performed from April 2nd to June 19th, 2019. The three replicate sets of the drying experiments were conducted from 2nd to April 4th, 8th to May 11th, and 17th to June 19th, 2019; for the 1st, 2nd and 3rd experimental drying run, respectively.

## 3.2 Materials and chemical reagents used

Raw materials, equipment and chemical reagents used in this study are indicated in Tables 1 and 2, respectively, below. Table 1 presents the raw materials used in the development of the ISD and SPE dryers (Table 1).

**Table 1: The raw materials used in the development of solar dryers**

| Type of Raw materials | Band/model | Details of Supplier | Range/Gauge | Accuracy |
|---|---|---|---|---|
| **Batteries - Sealed Lead Acid** | AGM Deep | Weize, USA | 12V, 12AH | - |
| **PVC Greenhouse plastics, UV** | PVC Polyethene | GT4 Plastics, USA | 6 mm | - |
| **Solar panels** | Poly-RV | Newpowa, Uganda | 160W; 12V | - |
| **Evacuating tube** | MVA6006 | Mityvac, UK | - | - |
| **Thermocouple (TEKCOPLUS)** | K-Type 4 | Tekcoplus, China | -50~700°C | ±2 |
| **Automated control system** | ThermostatH705 | Heagstat, Netherlands | - | - |
| **Suction fan** | - | - | - | - |
| **Anemometer** | YK-2005AM | REED Inst., USA | - | ±2 |
| **Galvanized Iron sheets** | Roofing-Colour | Roofing Ltd, Uganda | 3 mm | - |

The equipment was used in evaluating the drying performance of the ISD and SPE dryers and the OSD method (Table 2).

Table 2: The equipment used in evaluating the drying performance of the solar drying systems

| Type of equipment | Band/model | Details of Supplier | Range/Gauge | Accuracy |
|---|---|---|---|---|
| Proster Digital Vernier Caliper | PSTTL336 | Mitutoyo, Japan | 0-6" (150mm) | 0.01 |
| Digital weighing scale | GX4000 | A&D Co, Japan | 0.01 – 4100 g | 0.01 |
| Moisture analyzer | OHAUS-MB23 | OHAUS, USA | 3 – 20 g | - |
| Ice Plus LG Refrigerator | LRFVC2406D | Kuppet, China | up to -5 | 0.1 |
| Lutron data logger | DL-9601A | Kuppet, China | -200 – 350 ºC | ±0.1ºC |
| Solarimeter | KIMO | Solarmeter, China | 1 –1300Wm$^{-2}$ | ±1Wm$^{-2}$ |
| Thermocouples (T-type) | TT-T22S | Omega, UK | - | - |
| Relative Humidity sensors | HC2S3-L | Campbell Sci., USA | 0 – 100 % | 0.1% |
| A data logger | CR-3000 | Campbell Sci., USA | - | - |
| Automated weather station | JL-03-Q4 | Shandong, China | - | - |
| Hot air oven | DHG- 9055A | Memment, Germany | - | - |
| Blender | K400 | Matte Vintage, USA | - | - |
| Whatman filter paper | Whatman – 42 | Whatman plc, UK | 3 mm | - |
| Volumetric flask | Volume 250 cm$^{3}$ | Whatman plc, UK | - | - |
| Glass electrode pH-meter | Hanna HI9124 | Hanna Inc, Romania | - | - |
| KoneLab spectrophotometer | UV-Vis Kone 30i | Kone Corp, Finland | - | - |
| UV-Vis spectrophotometer | Agilent Cary-60 | Agilent Techn., USA | - | - |
| HPLC device | Perking 410 | Perking Elmar, UK | - | - |
| AAS devices | AA4530F | Chincan Co., China | - | - |
| Tissue homogenizer | PT3100-D | Polytron, Switzerland | - | - |
| Plastic syringe | Jinlong | Jinlong Co. Ltd, China | 1,5 to 25 ml | - |

Definition of symbols: (+) standard error / degree of measuring accuracy; (-) negative/ missing values; (mm) millimeters; (%) percentage; (ml) milliliters; ($Wm^{-2}$) watts per square meter; ($^oC$) degrees Celsius; and (g) grams.

The chemical reagents were used in assessing the effectiveness of using the solar drying methods (thus ISD and SPE dryers, and OSD method) on the nutritional content of the dried fruit (mango and pineapple) products (Table 3).

**Table 3: The chemical reagents used in the study**

| Type of chemical reagents | Specifications | Chemical Name | Molarity/specifications |
|---|---|---|---|
| **Fehling solution** | - | Acetonitrile solution | - |
| **Hydrochloric acid (1M)** | HCl | Ammonium molybdate | - |
| **Sodium hydroxide (2M)** | NaOH | Sulphuric acid ($H_2SO_4$) | 0.5M |
| **Glucose solution** | Sigma-Aldrich | Acetonitrile-methanol | $CH_3CN$ |
| **Methanol** | 50% | Sigma-Aldrich media | - |
| **Folin–Ciocalteu reagent** | - | Meta-phosphoric acid | $HPO_3$ |
| **Gallic acid** | - | 2,6- Dichlorophenol | 2,6-Indophenol dye |
| **Sodium carbonate solution** | 7.5% | Acetonitrile solution | - |

### 3.3 Fabrication of the improved passive and active mode solar dryers

In this study, a modified passive-mode hybrid solar dryer dubbed ‘Improved Solar Dryer (ISD)’ unit was prototyped. A conventional active mode hybrid solar dryer dubbed: ‘Solar Photovoltaic and Electric (SPE)’ dryer was also fabricated. The two types of solar dryers, namely the ISD and SPE dryers, were fabricated because they use different energy resources with passive and active-active modes of operations, respectively. The ISD unit was fabricated to solve the drying needs of the local subsistence farmers and resource-constrained agro-processors in remote locations without electricity and entirely depend on renewable solar energy to dry produce. In contrast, the SPE dryer uses either alternating current with a backup source of direct current from the solar panels to facilitate continuous drying of bulk products, including during the night shifts or during rainy and cloudy conditions without sunshine. The SPE dryer, therefore, targets commercial farmers and processors with bulk fruit produce to be dried continuously for marketing. Both the ISD and SPE dryers were fabricated at the National Livestock Resources Research Institute, NaLIRRI (0° 31’26 “N; 32°37’10 "E) at Nakyesasa in Wakiso district, Uganda. The dryers were taken to the NM-AIST University in Arusha, Tanzania, for drying performance studies.

## 3.4 Fabrication of a novel passive-mode 'Improved Solar dryer (ISD)' prototype

### 3.4.1 The Improved Solar Dryer prototype design and the principle of operation

Unlike the hybrid passive-mode solar dryers that exist on the world market, the design of the novel ISD prototype consisted of two distinct solar heat transfer components, namely, a modified 'solar energy concentrator (SEC)' plate and an improved 'direct solar drying (DSD)' cabinet. Figure 3 presents a schematic illustration of the design and principle of operation of the ISD unit. The schematic representation of the design of the SEC and DSD components are also shown in parts A and B of the ISD unit, respectively (Fig. 3).

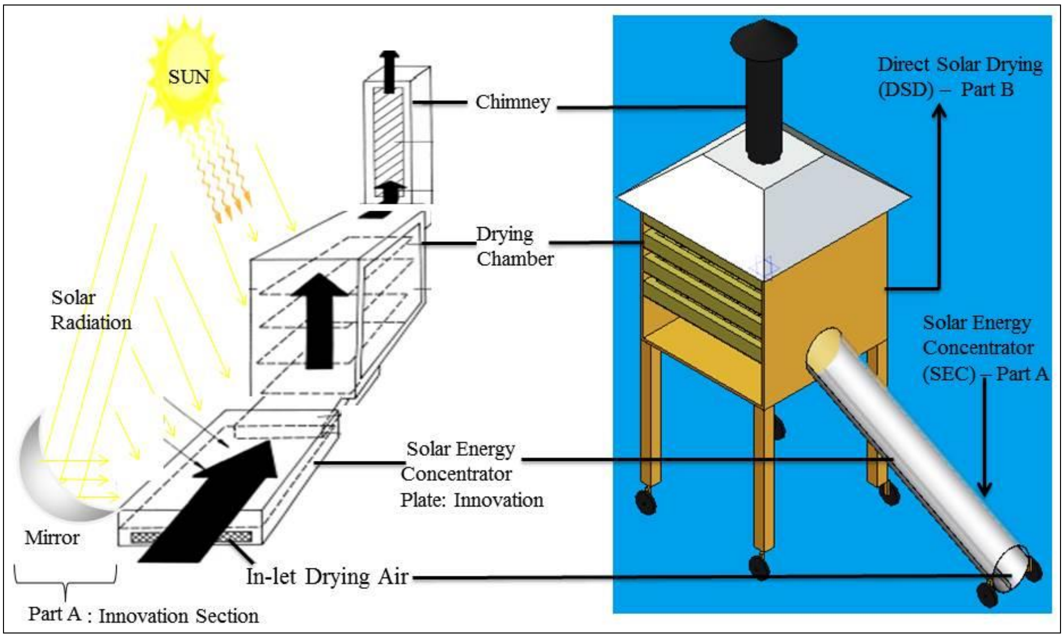

**Figure 3: Schematic representation of the design of the improved solar dryer (ISD) unit**

The modified SEC and DSD components employed both direct and indirect solar thermal transfer mechanisms, respectively. Thus, both the SEC and DSD components facilitated the simultaneous transfer of solar energy into the ISD unit. In this context, combining the indirect and direct solar energy transfer mechanisms into a single ISD unit enhanced its internal solar thermal energy as well as the drying air temperatures within the ISD drying cabinet.

The design of the SEC component consisted of multiple 3D metallic solar energy concentrators. The metallic concentrators were arranged in series against a blackbody metal. This configuration served to maximize retention of the solar thermal energy within the SEC section, which was directly transmitted into the DSD component by natural convection. The concentration of the incoming solar radiation energy and its retention in the modified SEC system was based on the working principle of the indirect solar energy transfer by natural convection; as it was the case for numerous conventional hybrid indirect solar dryers (Amer et al., 2010; Hii et al., 2012; Kumar et al., 2016).

On the contrary, the design of the DSD component consisted of a modified food drying cabinet. The DSD component was made of a drying cabinet which was enclosed with a transparent UV-treated greenhouse plastic cover material. The greenhouse cover material was employed to exclusively allow entry of incident high-speed short-wavelength solar radiations into the ISD drying cabinet. The incident radiations further enhanced the internal energy and temperature of the product drying air within the DSD section (thus ISD drying cabinet).

During this process (of increasing internal energy and warming of the product drying air within the DSD section by the incident radiations), the shortwave solar radiations were transformed into slow long-wave radiations. And as a result, the greenhouse plastic cover material enclosing the DSD section was simultaneously employed to avert the escape of the transmitted slow long-wave solar thermal radiations out of the DSD component into the atmosphere. The process of trapping and transmitting high-speed shortwave solar radiations into slow long-wave thermal radiations is referred to as the greenhouse effect (Krawczyk *et al*., 2012; Kumar *et al*., 2016; Tubiello *et al*., 2015).

Designs similar to the DSD component were utilized to achieve comparable greenhouse warming effects in the conventional indirect solar driers developed by Chauhan and Kumar (2016), Hii *et al*. (2012) and Kumar *et al*. (2016), which were also employed to boost the food drying process. The greenhouse warming effect was further exploited to boost both the drying air temperatures and internal thermal energy in the drying cabinets of the conventional solar dryers (Chauhan & Kumar, 2016; Kumar *et al*., 2016).

### 3.4.2 Assembling the physical Improved Solar Dryer prototype

A medium-scale ISD unit (Fig. 4) was developed by assembling and adjoining five major dryer components, namely: a produce drying cabinet, a modified metallic solar collector plate, and stands. The wooden and metallic materials used in the fabrication of the dryer components were procured from local suppliers. The selection of the materials was based on low cost and availability in the local stores, including the quality and suitability of the materials for use in the specific ISD dryer components. After procurement of the materials, each of the five dryer components was designed and fabricated separately, as described below.

A modified solar collector plate was made of a metallic flat-plate was an improved version of a typical solar collector plate used in conventional solar dryers (Belessiotis & Delyannis, 2011; Hii *et al*., 2012; Kumar *et al.*, 2016); where the solar absorber plate was replaced with auxiliary metallic solar concentrators. The modified solar collector plate was a rectangular flat plate with dimensions 1 m by 7 cm by 2.2 m for the width, height, and length, respectively. The main body of the solar concentrator plate was made from galvanized iron sheets, which were already black in colour (Fig. 4), was used to boost its solar absorption capacity. The plate was modified with 15 pieces of cylindrical metallic solar concentrators to increase its capacity in absorbing and retaining the additional solar thermal energy. Each of the metallic concentrators was cut from a single galvanized steel tube at 5 cm and 2.3 m in diameter and lengths, respectively. The metallic solar concentrators were arranged in parallel to each other inside the solar collector plate and were covered with inelastic transparent plastic glass materials to maximize absorption of the incident solar radiation (Fig. 4). Similarly, the bottommost layer of the modified solar collector plate was aligned with a white silver plastic material to reflect the internally transmitted solar radiations towards the multiple focal lengths. The exterior base and sides of the modified solar collector plate were insulated with 20-mm Styrofoam sheets.

The air flows through the ISD dryer by natural convection and exits the dryer via the chimney. The natural convection criterion was used in designing the airflow system in the ISD dryer. A lightweight chimney was made by folding a galvanized iron sheet into one cylindrical tube. The chimney tube was folded into 15 cm in diameter and was cut at 0.8 m in length (Fig. 4). Four metallic legs for the ISD were also made by cutting stainless steel at 0.6 m lengths. Four produce drying trays were made by cutting high-quality plywood into a surface area of 0.95 $m^2$ and 0.5 cm by width. A perforated aluminium wire mesh was cut into a 0.95 $m^2$ area was affixed to the bottom of the wooden produce drying trays.

A medium-scale produce drying cabinet was made of metal frames from the galvanized steel materials with the same dimensions and configurations as the modified solar collector plate. The base of the drying cabinet was adjoined to the modified solar collector plate. The sides of the drying cabinet were clad with a specialized non-perforated UV-treated greenhouse plastic-film material to insulate the cabinet, including the cabinet door (Fig. 4).

Four tray holders were affixed on the frames inside the drying cabinet at 0.25-meter intervals. The four removable produce drying trays holding the fresh produce to be dried are mounted on the tray holder. The total surface area of the ISD drying cabinet was 1 m$^2$, and the effective drying area was 0.95 m$^2$ for the trays. A chimney was mounted on top of the drying cabinet in a top-bottom orientation while the four legs (made of metals) were fixed at the bottom of the drying cabinet to raise the unit 0.6 m above the ground (Fig. 4).

**Figure 4: The improved solar dryer (ISD) prototype fabricated**

Where; a) the multiple metallic solar thermal energy concentrators, b) the ISD with a modified solar concentrator, c) assembled physical ISD with cabinet enclosed with a greenhouse cover.

All the major components of the ISD system were assembled to make a complete ISD unit. The components could be easily detached from the assembled ISD unit to ease transportation and could easily be re-assembled at the target destination.

### 3.5 Fabrication of the conventional active mode hybrid solar dryer

The conventional active mode hybrid photovoltaic solar dryer with an auxiliary electric thermal backup system hereafter called: a 'Solar Photovoltaic and Electric (SPE)' dryer was fabricated following protocols outlined by Samimi-Akhijahani and Arabhosseini (2018). Like the ISD unit, a medium-scale SPE dryer was fabricated. The SPE dryer was made of a drying cabinet and four metallic stands of the materials, dimensions, and configurations as the ISD unit.  Additional components of the SPE dryer included; 4 batteries, an air-evacuating tube, two solar panels (of 60 watts), a suction fan of 12-Volt); an automated control system, a thermocouple, a charge controller, and an auxiliary electric thermal backup system (Fig. 5).

**Figure 5: The major components of the Solar Photovoltaic and Electric (SPE) dryer.**

Where: 1) Evacuating tube, 2) suction fan, 3) Solar panels, 4) automated-control systems, 5) batteries, 6) Thermocouple, 7) drying cabinet, 8) drying trays, 9 and 10) stainless-steel mesh trays.

All the above-listed materials were bought from local supply stores and were assembled into the SPE dryer. During assembling, a battery cage was welded and attached to the metal stands. Four batteries were put in the stands, and a drying cabinet was affixed on top of the dryer stands. The chimney and external suction fans were attached to the top and bottom of the drying cabinet (Fig. 5). The air flows through the SPE dryer by forced convection and exits the dryer via the chimney.

Solar panels were displayed in the open round and connected to both the batteries and drying cabinet using electrical wires. The direct current collected by the solar panels was backed up in the batteries to facilitate nonstop drying of fresh produce. A thermocouple and anemometer were attached to the automated control system and were also integrated with the drying cabinet to control the internal drying conditions. Thus, the circulation of the drying air in the drying cabinet was pre-set and controlled by adjusting the rotation and speed of the suction fan using an anemometer. The rotation and speed of the suction fan were pre-set at 50% and 15ms$^{-1,}$ respectively, and these settings regulated the produce drying temperatures and humidity in the drying cabinet.

### 3.6 Experiments to evaluate the drying performance of the solar dryers, and the open sun drying method

In this study, selected fruits, namely mangoes and pineapples, were used to evaluate the drying performance of the novel passive-mode ISD dryer and the active mode SPE dryers. The drying performance of the individual ISD and SPE dryers was assessed and later compared with that of the traditional OSD method.

### 3.6.1 Preparation of the selected fruit samples for the drying experiments

One cultivar of pineapple (*Ananas comosus* cv. *Smooth Cayenne*) and one cultivar of mango (*Mangifera indica* cv. *Bire*) were selected for this study. These cultivars were selected because they are the most preferred cultivars by farmers, and they also have substantial amounts of vital nutrients and phytochemicals (Jongen, 2002). A total of 60 pineapples (whose average weight was 1.3 kg) and 90 mango fruits (whose average weight was 0.95 kg) were bought from a market in Tengeru town in Arusha, Tanzania. Only the mature and ripe fruits without any visible physical damage were selected from the same stall, and the selection was based on uniformity in size and firmness. Fully ripe fruits that were yellowish-brown in colour, at their climacteric ripening stages, were selected and picked to achieve optimal drying results. This approach was adopted because the aim of the study was to test the drying performance of ISD and SPE dryers rather than product development from the dried fruits (mangoes and pineapples). The selected fruits were put in a cool box and were transported to the Life Sciences Laboratory at the NM-AIST University for further preparation and processing. It took 15 minutes to transport the fruit samples from the Tengeru market to the NM-AIST Life Sciences lab for sample preparation.

The fruit samples were removed from the cool-box, cleaned with running potable water, and were afterwards drained under ambient weather conditions. External non-edible portions of both the mango and pineapple samples were peeled off using a kitchen knife. Edible portions of the fruit samples were sliced at standard cross-sectional portions of 3 mm thickness (Fig. 6), as was the case for the fruit drying studies done by Kumar *et al*. (2016) and Tunçkal *et al*. (2018). A digital vernier calliper and a metallic slicer were employed to guide the precise cutting of the pineapple and mango samples into uniform oval-shaped slices of 2.5 cm in diameter and 3 mm thickness (Fig. 7). No pre-treatment of the samples was done prior to drying. Although pre-treatment could enhance the nutritional content, the focus of the present study was to assess the performance of the dryers in relation to the retention capacity of both sensory quality and nutritional content in the dried products. In this regard, the sensory and nutritional profiles of the fresh fruits were taken as baseline data for assessing the performance of the two dryers.

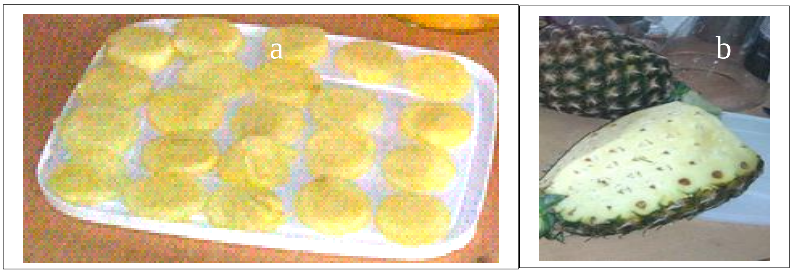

**Figure 6: Some of the fresh pineapples and their slice samples**

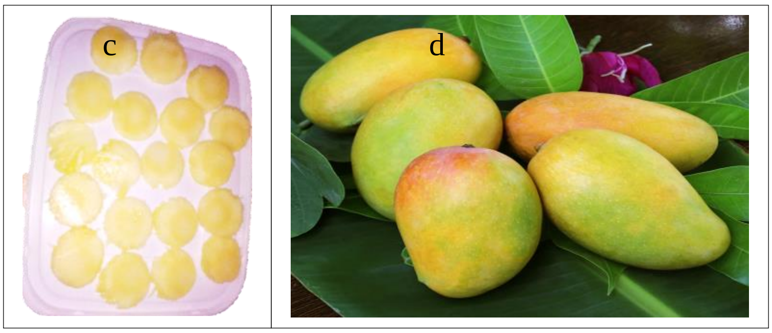

**Figure 7: Some of the fresh mangoes and their slice samples**

Ten replicate batches of both the mango and pineapple slice samples were prepared and put on distinct plastic plates. Each batch was made of 3 plastic plates, and each plate had 18 identical pieces of mango and pineapple slices. The initial mass and moisture of the fruit slice samples were measured using a digital weighing scale and moisture analyzer, respectively. About 3 to 5 slices of the mango and pineapple samples were randomly picked from each plastic plate, put on the crucible, and weighed. The mean mass and moisture of the fresh slice samples were computed and recorded. The 1st batch of the slice samples was kept in its fresh form maintained at -4°C in a refrigerator and hence provided baseline parameters for evaluating the sensory quality attributes and nutritional composition of the solar-dried fruit products. The remaining nine batches of the mangoes and pineapple slices were dried under the three solar drying methods.

### 3.6.2 Experimental procedure for drying mango and pineapples samples

The nine batches of the pineapple and mango slice samples were simultaneously dried in 3 replicate sets of 2 batches each under the three solar drying methods (thus ISD and SPE dryers, and OSD methods). Standard protocols for RCBD experiments, as described by Mead (2017), were followed during the drying operations of the fruit samples. The solar drying methods were the experimental units (or groups), whilst the fruit types (mangoes and pineapples) were the treatment variables. A uniform size (of thickness - 3 mm; diameter - 2.5 cm) of the slice samples was employed as the experiment blocking factor.

On each day of dry experiments, preparation of both the pineapple and mango slice samples was started by 7:00 AM. The fruit samples were cleaned, peeled, and cut into 3 mm uniform slices. The produce drying trays got from the ISD and SPE dryers and loaded with fresh mango and pineapple slices. In the OSD method, the slice samples were spread on a tarpaulin covering an area of 1 $m^2$ enclosed in a perforated white transparent food drying mesh. The tarpaulin and mesh were put on wooden stands and were elevated at 1.5 meters above the ground. Elevating the tarpaulin served to reduce contamination of the fresh fruit slices during the OSD drying process. A uniform loading density of 36 pieces (approximately 0.85 kg) of the fresh sample slices for every 1 $m^2$ of the drying area was maintained across the three solar drying methods, as was the case for the food drying experiments conducted by Tibebu (2015).

By 8:00 AM, preparation of the slice samples and experiment setup was completed, and drying of the mango and pineapple slice samples started. All the replicate drying cycles were started from 8:00 AM to 6:00 PM, which is the mean day length under identical ambient weather conditions, including cloud conditions and wind speed. The mean solar radiation estimates for the typical 1st, 2nd, and 3rd drying days were 3590, 3398, and 3485 $W/m^2$, respectively. Drying was continued until the samples attained moisture content of 10% or lower; because it is the optimum safe storage moisture content level for most fruits, including mangoes and pineapples (Wills & Golding, 2016). In the event that the sample drying was to continue for the next day, the partially dried cultivar samples were kept overnight in sealed air-tight plastic bags to retard any further dehydration and moisture re-absorption in the partially dried fruit products.

In all the drying methods, the internal drying conditions, including the drying air temperatures, relative humidity (RH), solar thermal energy, and mass of the fruit slice samples, were recorded after every 30 minutes; as the fruit drying progressed until the end of the day (at 6 PM). Three sets of T-type thermocouples and RH sensors were each installed, along with the drying trays of the ISD and SPE dryers and OSD methods. The thermocouples and RH sensors were connected to a Lutron data logger to record the internal drying air temperatures and RH data, respectively, and data were retrieved through RS232 cables, which were connected to a computer. The solar thermal energy of the ISD and SPE dryers and that of the OSD method was measured and recorded using an integrating solarimeter. Similarly, data for daily ambient weather conditions during the experiments, namely ambient air temperatures, RH, and solar radiation energy, were recorded remotely using the digital Lutron thermometer, RH probe, and the solimeter, respectively. These instruments were embedded in an automated weather station instrument installed at the Nelson Mandela African Institution of Science and Technology (which was the experimental drying site).

Moisture lost from the fruit slice samples was estimated by weighing on the digital scale. The drying trays were unloaded from the drying cabinet of the ISD and SPE dryers. Five pineapple and mango slice samples were marked for repetitive measurements and weighed after every 30 minutes. The drying time was recorded using a digital stopwatch, and the measurement continued until there was no noticeable decline in weight for each successful measurement. The process of unloading and reloading the trays during the weight measurements was hurried, and it took between 40 to 55 seconds for each measuring cycle. The aforesaid procedures were repeated to measure the moisture loss from the fruit slice samples dried under the traditional OSD method.

## 3.7 Evaluating the drying performance of the solar dryers, and the open sun drying method

The drying performance of the ISD and SPE dryers and OSD methods were evaluated using solar thermal energy, drying air temperatures, moisture content, drying rate, and energy-use efficiency. These parameters were selected because they are leading performance indicator parameters for any primary food drying and other agro-processing systems (Bhardwaj *et al*., 2017; Mustayen *et al*., 2014; Phadke *et al*., 2015; Wankhade *et al*., 2013). The solar thermal radiation energy and drying air temperatures were recorded directly during the solar drying experiments using the solarimeters and thermocouples, respectively, as described above.

### 3.7.1 Determination of moisture content

The moisture content of the fruits (mango and pineapple) slice samples was calculated on a wet basis method (Bhardwaj *et al*., 2017; Phadke *et al*., 2015; Wang *et al*., 2018; Wankhade *et al*., 2013). The moisture content was estimated from the mean weight loss measurements of the slice samples taken during the drying process, and it was expressed as the mean weight of the weighed slice samples per unit weight of the fresh sample (Equation 1). During the drying process, the slice samples were temporarily removed from the ISD and SPE dryers and OSD methods and weighed on a digital weighing scale. The initial and final mass of the dried slice samples were recorded every 30 minutes. The moisture content of the slice samples was calculated as a ratio of the difference in the initial and final mass of the dried slice samples, relative to 100 g of the fresh slice samples (Equation 1); as was the case for Wankhade *et al*. (2013), and Wang *et al*. (2018).

$$\text{Moisture Content, MC}\left(\frac{\text{g}}{100\text{g}}\right) = 100 - \left(\frac{M_1(100 - M_o)}{M_2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 1}$$

Where; MC is moisture content (on a wet basis) at any time (t), $M_o$ is the mass of the fresh mango and pineapple cultivar samples before drying, $M_1$ and $M_2$ are the initial and final mass of the cultivar samples during the weight loss measurements at any drying time (t); respectively.

### 3.7.2 Determination of the drying rate

The drying rate was evaluated by dividing the moisture content of the pineapple and mango slice samples and the time intervals taken to dehydrate the sample, as was the case for Wankhade *et al*. (2013) and Bhardwaj *et al*. (2017). Thus, the drying rate was calculated as a ratio of the difference in the mass of the fruit (pineapple and mango) slice samples weighed during a definite time interval between being drying times $t_2$ and $t_1$ (Equation 2).

$$\text{Drying Rate }(gMin^{-1}) = \frac{\Delta\text{Mass (g)}}{\Delta\text{time (Minutes)}} = \frac{(M_1 - M_2)}{(t_1 - t_2)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 2}$$

Where; $M_1$ and $M_2$ are the initial and ending mass of the slice samples during the repetitive weight measurements, respectively. Similarly, $t_1$ and $t_2$ were the definite drying times in minutes (Min) to dehydrate the samples from $M_1$ to $M_2$.

### 3.7.3 Determination of the drying efficiency

The drying efficiency of the ISD and SPE dryers and OSD methods was estimated using the energy flux method (Navale *et al.*, 2015; Wankhade *et al.*, 2013). Drying efficiency was evaluated using the solar thermal energy, drying time, and drying surface area of the fruit samples. The efficiency was calculated as a ratio of the thermal energy employed in actual drying the fruit (pineapple and mango) slice samples to the total solar energy received or supplied to the drying ISD, SPE, and OSD systems (Equation 3); as it was the case for the Navale *et al*. (2015) and Wankhade *et al*. (2013).

$$\text{Food Drying Efficiency, FDE} = \frac{\sum M \times L_V}{\sum I_t \times A_c \times t} \text{x } 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 3}$$

Where; M is the total mass (kg) of moisture dehydrated from the weighed slice samples, Lv is the latent heat of vaporization of water (Lv= 2320 kJ/kg), $I_t$ is total thermal energy recorded for the entire drying process ($Wm^{-2}$), $A_c$ and t are surface area ($m^2$) and drying time (s) taken by each method.

## 3.8 Determination of the nutritional content and chemical composition of the selected fruits

In assessing the effectiveness of using the ISD and SPE dryers, and OSD methods on both fresh and the dried fruits, namely mangoes and pineapples, the following nutritional and chemical parameters were analyzed: moisture content, dry matter, total carbohydrates, total titratable acidity, phenols, total sugar content, mineral content, vitamin C and beta carotene content.

### 3.8.1 Determination of Moisture content

The initial mass and moisture of the fresh mango and pineapple slice samples were measured before drying using the digital weighing scale and moisture analyzer, respectively. The moisture content of the dried fruit slice samples was determined using the wet-basis method. The fresh slice samples were dried until they attained a constant weight using the three solar drying methods, namely the ISD and SPE dryers and OSD methods.

### 3.8.2 Determination of Dry matter content

The dry matter content of the mango and pineapple slice sample products was evaluated using a dry basis method while following protocols described by the Association of Official

Analytical Chemists, AOAC methods (Nielsen, 2017); with slight modifications made by Teye *et al*. (2011). The final mass of the samples products dried using the ISD and SPE dryers, and OSD methods were determined by re-weighing the samples on the digital weighing scale. The dry matter content of the solar-dried slice samples was calculated as a % ratio of the mass of the samples before and after drying.

### 3.8.3 Determination of Total carbohydrates

Total carbohydrate content in the fresh and dried slice samples for both mangoes and pineapples was determined using the titrimetric procedures while following the standard AOAC protocols (Nielsen, 2017). Exactly 5 g of both the fresh and dried slice samples were measured using the digital weighing scale. The samples were put in porcelain crucibles and mixed with 5 ml of 1M hydrochloric acid (HCl). The mixture was heated for 3 to 5 minutes to complete acid hydrolysis. About 20 ml of 2M NaOH (sodium hydroxide) was added, and the mixture was neutralized by the addition of 10 ml of Fehling solution. A standard glucose (Sigma-Aldrich) solution was used to build calibration titrimetric points and curves (as standards). The total carbohydrates content of the sample solutions were estimated and expressed as g of glucose equivalent per 100 g of the samples as guided by the standard calibration curves.

### 3.8.4 Determination of Total acidity

The total acidity was determined using a potentiometric titration method, where the acid content in the slice sample solutions was neutralized following the protocols outlined by Polish (1990). Exactly 25 g of the mango and pineapple slide samples, each dried using the ISD and SPE dryers, and OSD methods were homogenized by crushing into powder using a blender. The homogenized mixture of the sample powder was put in a volumetric flask (of 250 $cm^3$) and was diluted with distilled water up to the 250 $cm^3$ mark. The mixture was warmed in a water bath for 30 minutes on a stove. Afterwards, the mixture was re-diluted with distilled water to the original 250 $cm^3$ volume and was filtered using a Whatman filter paper. Exactly 25 ml of the filtrate was put in a beaker and titrated with 0.1M NaOH solution at room temperature (of 26 $^oC$). During titration, a glass electrode pH meter was dipped into the solution, and titration was stopped when a pH of 8.0 was achieved. The volume of the NaOH used corresponded to the total acidity of the sample, and the titrimetric values were expressed as m-moles per 100 g of the dried products.

### 3.8.5 Determination of Total phenols

The total phenolic content (TPC) from the mango and pineapple fruit samples were estimated using Folin–Ciocalteu procedure (Lester *et al.*, 2012; Singleton *et al.*, 1999); and gallic acid as the standard solution while following standard protocols by the AOAC methods (Nielsen, 2017). The mango and pineapple slice sample products dried using the ISD and SPE dryers, and OSD methods were homogenized by crushing into powder form using the blender. The homogeneous sample was analyzed using a KoneLab Spectrophotometer. The TPC in the homogeneous sample was extracted by shaking 0.5 g of the samples with 10 ml of methanol and HCl at concentrations of 50% and 1M, respectively, for 30 minutes. The TPC extraction process was repeated twice, and the resultant supernatants were combined into one beaker. The solution was filtered using the Whatman filter paper, and the extracts were kept in the refrigerator, which was kept at -20 $^{o}$C until the samples were analyzed.

During analyses, 0.5 ml of the sample extracts were shaken with 2.5 ml of the Folin-Ciocalteu medium (Lester *et al.*, 2012), and the solution was incubated at 37 $^{o}$C in the oven for 1 minute. The solution was mixed with 2 ml of 7.5 % $Na_2CO_3$ (Sodium carbonate) solution. The resultant mixture was again incubated at 30 $^{o}$C for 30 minutes, and absorbance readings of TPC samples were measured calorimetrically using the KoneLab spectrophotometer. The spectrophotometer was set at 760 nm, and the TPC readings were measured against standard calibration curves of the gallic acid. The TPC readings were expressed as mg of the gallic acid equivalents per 100 g of the fresh slice samples.

### 3.8.6 Determination of Total sugar content

The total sugars (thus glucose, fructose, and sucrose) content in the fresh and dried mango and pineapple samples were analyzed using the high-performance liquid chromatography (HPLC) procedures; as was the case for the sugar analyses performed by Sánchez-Mata *et al.* (2002), and Zaky *et al.* (2017). The HPLC analysis was performed while following slight modifications outlined by Sharma *et al.* (1988). Exactly 2 g of the fresh sample and that dried using the ISD and SPE dryers and OSD methods were put in a beaker and were serially diluted with 700 µL of distilled and de-ionized water. Five 5 ml of 0.5M Sulphuric acid ($H_2SO_4$) was added to the sample solution, followed by 20 ml of $CH_3CN$ (Acetonitrile of methanol). The solution was mixed to homogeneity for 1 hour using a tissue homogenizer device and afterwards centrifuged for 15 minutes at 3600 rpm. The supernatant was removed using a plastic syringe (of 10 ml) and the Whatman filter paper. An additional 1 ml of the supernatant was further filtered into the HPLC vial. The Vial was sealed with a septum and a plastic cup until the HPLC analyses were done.

The total sugar content was determined by injection of 20 µL of each sample solution into the HPLC using a LiChrospher 100-$NH_2$ (5 µm; 4×4 mm pre-column; number: 1.50966.0001); together with the LiChrospher 100-$NH_2$ (4x250 mm separation column; number: 50834.0001). The HPLC column temperature was using thermostat Jetstream-2 and maintained at 20$^o$C. A mobile phase consisting of 80:20 (V/v) of distilled water to acetonitrile solution was also maintained at a constant flow rate of 1 ml per minute.

### 3.8.7 Analysis of the mineral content

In assessing the effectiveness of using the ISD and SPE dryers, and OSD methods on the mineral composition of the dried mango and pineapple slice sample products, the following macro and micro mineral elements were analyzed: phosphorus (P), calcium (Ca), iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn). Both the macro and micro mineral elements were analyzed using an Atomic Absorption Spectrophotometer (AAS); while following the protocols of Allen (1989) and Steve (2016), respectively. The P content in the sample was analyzed using the AAS machine, which was set at 420 nm, after treating the samples with ammonium molybdate followed by ascorbic acid. The K and Ca were estimated using a flame photometer while following the standard protocols outlined by Allen (1989). Similarly, the micro-mineral elements, namely; Fe, Cu, Zn, and Mn, were analyzed using the ASS machine while following the standard procedures outlined by Steve (2016).

### 3.8.8 Determination of beta carotene content

β-carotene content was analyzed using a modified ultraviolet scanning method while following the protocols described by Prior *et al*. (2005). The carotenoid content in the fresh and dried fruit samples was quantified by the KoneLab spectrophotometer, which was set at 450 nm. Sigma-Aldrich media were selected as the standard media for the β-carotene and were used to build the standard calibration curves for which the carotenoid levels in the samples were measured. The aggregate carotenoid content in the fresh and dried samples for the mango and pineapple slices was quantified as µg of β-carotene equivalent per 100 g of the fruit sample.

### 3.8.9 Determination of Vitamin C content

Vitamin C (L ascorbic acid) was determined using the colourimetric method (Ranganna, 1986). The mango and pineapple samples were mixed with 50 ml of 3% metaphosphoric acid ($HPO_3$) and diluted with an additional 50 ml of $HPO_3$ acid solution. Each fruit sample mixture was homogenized using the tissue homogenizer. The resultant slurry was centrifuged and, afterwards, filtered using the Whatman filter paper. Exactly 5 ml of the filtrate were mixed with 10 ml of 2,6-dichlorophenol-indophenol dye, and its absorbance was measured by the spectrophotometer. The ascorbic acid content in the sample solution was estimated in mg per 100g of the standard sample solution (Equation 4).

$$\text{Ascorbic Acid}\left(\frac{\text{mg}}{100\text{g}}\right) = \frac{\text{Ascorbic acid absorbance} \times \text{Volume of HPO}_3\text{ made up} \times 100}{\text{The volume of sample analyzed} \times \text{sample mass} \times 1000} \text{ .... Equation 4}$$

## 3.9 Determination of the sensory quality attributes of the dried fruit products

The effect of using ISD and SPE dryers and OSD methods on the sensory quality attributes of the dried fruit (mango and pineapple) products was assessed following a standard hedonic scale procedure, as outlined by Civille *et al*. (2015). Twenty panellists were selected from traders in the Tengeru market in Arusha following a purposive random sampling procedure. The panel had ten female and male evaluators. Their age ranged from 20 to 55 years, with the mean and standard deviation of 38 and 15 years, respectively. The number, sex, and age of the panellists were consistent with a representative panel of evaluators recommended by Civille *et al*. (2015), who recommended that a typical panel of 14 judges; as large enough to have reproducible results.

The sensory quality attributes of the dried mango and pineapple slices evaluated included aroma, taste, colour and general acceptability. Each of the panellists was given the mango and pineapple slice samples dried under the ISD and SPE dryers and OSD methods to taste and make an independent evaluation. They were guided to make their evaluation and rank the sensory quality attributes of the solar-dried products based on the verified 9 points of the hedonic scale (Civille *et al*., 2015). The 9 points included: 1 = dislike extremely; 2 = dislike very much; 3 = dislike moderately; 4 = dislike slightly; 5 = neither like nor dislike; 6 = like slightly; 7 = like moderately; 8 = like very much; and 9 = like extremely.

### 3.10 Statistical analyses

Data obtained were processed for mean values and analyzed for the existing sources of variation in the drying parameters using Analysis of Variance (ANOVA) in GenStat statistical software (Payne *et al*., 2009). A one-way ANOVA was used to compare the means for the drying variables and nutritional parameters between the drying methods. The means were separated using Tukey’s HSD test, and the statistical significance was determined at a 5% ($p<0.05$) level.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 The passive-mode Improved Solar Dryer and active mode Solar Photovoltaic and Electric dryer fabricated

The developed ISD unit (Fig. 8a) employed novel configurations and design combinations of both the direct and indirect hybrid solar heat and thermal energy transfer mechanisms into a single modified passive–mode hybrid dryer unit. This gave the physical ISD unit an exclusive capacity to concentrate extra incident solar radiations, which were, afterwards, converted into thermal energy in the product drying cabinet. The supplementary thermal energy was employed in enhancing the food drying process. The physical ISD unit was, therefore, an improved version of the typical passive mode hybrid solar dryer. The unit simultaneously employed the direct and indirect solar thermal energy transfer mechanisms by natural convection to dry the fresh and succulent fruit produce.

**Figure 8: Physical prototypes of the ISD unit (a) and SPE dryer (b) developed**

On the other hand, the SPE dryer unit (Fig. 8b) was designed to utilize a combination of solar photovoltaic system and electricity into a single active mode hybrid dryer system when drying the produce. Unlike the ISD unit, the SPE dryer was equipped with a complimentary electric backup system, which also facilitated continuous drying of the produce. Thus, the

SPE dryer was capable of drying food even under cloudy and rainy weather periods or during night shifts, when there is very limited insolation and/ or no direct sunshine.

## 4.2 Drying performance of the individual solar dryers and open sun drying method

The drying performance of the ISD and SPE dryers was evaluated against the OSD method. The performance indicator parameters were; drying thermal energy, drying air temperatures, moisture content, drying rate, and drying efficiency. Table 4 shows the Analysis of Variance (ANOVA) for the general performance of the ISD and SPE dryers and the OSD method.

**Table 4: ANOVA showing general performance of the solar drying methods**

| **Response: Drying rate(g/min)** | | **Mangoes** | | **Pineapples** | |
|---|---|---|---|---|---|
| ***SOV*** | ***Df*** | ***Mean Sq.*** | ***P*** | ***Mean Sq.*** | ***P*** |
| Group (*Drying method*) | 2 | 1.906 | 0.003$^{**}$ | 2.63978 | 0.000** |
| Treatment (*Fruit type*) | 1 | 0.00007 | 0.987$^{ns}$ | 0.00004 | 0.990$^{ns}$ |
| Group: Treatment | 2 | 0.01473 | 0.947$^{ns}$ | 0.01648 | 0.943$^{ns}$ |
| Residuals | 748 | 0.27051 | | 203.917 | |

*Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1* $^{ns}$ *non-significant*

*SOV* =Source of Variation, *Df* = degree of freedom, *Mean Sq.* = mean sum of squares, *p = statistical significance at 5%,* Group = solar drying methods (ISD and SPE dryers, and OSD), Fruit type = pineapple & mango; Group: Treatment refers to any interaction effect between the treatment or grouping variables.

Results indicate that there were significant ($p<0.05$) variations in the drying performance of the three drying methods, namely, OSD method, ISD, and SPE dryers (Table 4). The results concur with performance results exhibited by several hybrid solar dryers studied on different fruits, including longan and banana by Janjai *et al*. (2009); melons by Aktaş *et al*. (2016); tomatoes by Ringeisen *et al*. (2014); and peer fruits by Lahsasni *et al*. (2004). These studies also reported significant variations in the drying performance between the passive and active mode hybrid solar dryers, regardless of the type of fruit products dried.

### 4.2.1 The solar thermal energy and drying air temperatures

Figure 9 compares the mean variations in the ambient temperature and incident solar radiation energy for the OSD method as well as solar thermal energy and drying air temperatures achieved by the ISD and SPE dryers during the three replicate drying cycles. The drying experiments were performed outdoor. The mean daily ambient temperature and relative humidities were 26.8 $^{o}$C and 26.7 %, respectively. These were also the same mean temperatures and relative humidity values recorded for the traditional OSD method.

The mean relative humidity achieved by the ISD and SPE dryers during the entire drying process was 25.8 and 24.6%, respectively. The mean drying air temperatures achieved by the ISD and SPE dryers were 27.7 and 40.3 °C, respectively. The mean solar thermal energy recorded for the ISD dryer, SPE dryer and OSD method were 4795, 5994 and 3595 W/m$^2$ (Watts per square meter), respectively. During the fruit drying process, the solar thermal energy and drying air temperatures for the three solar drying methods increased with a cumulative intensity of the ambient temperatures and solar radiation, and vice versa (Fig. 9).

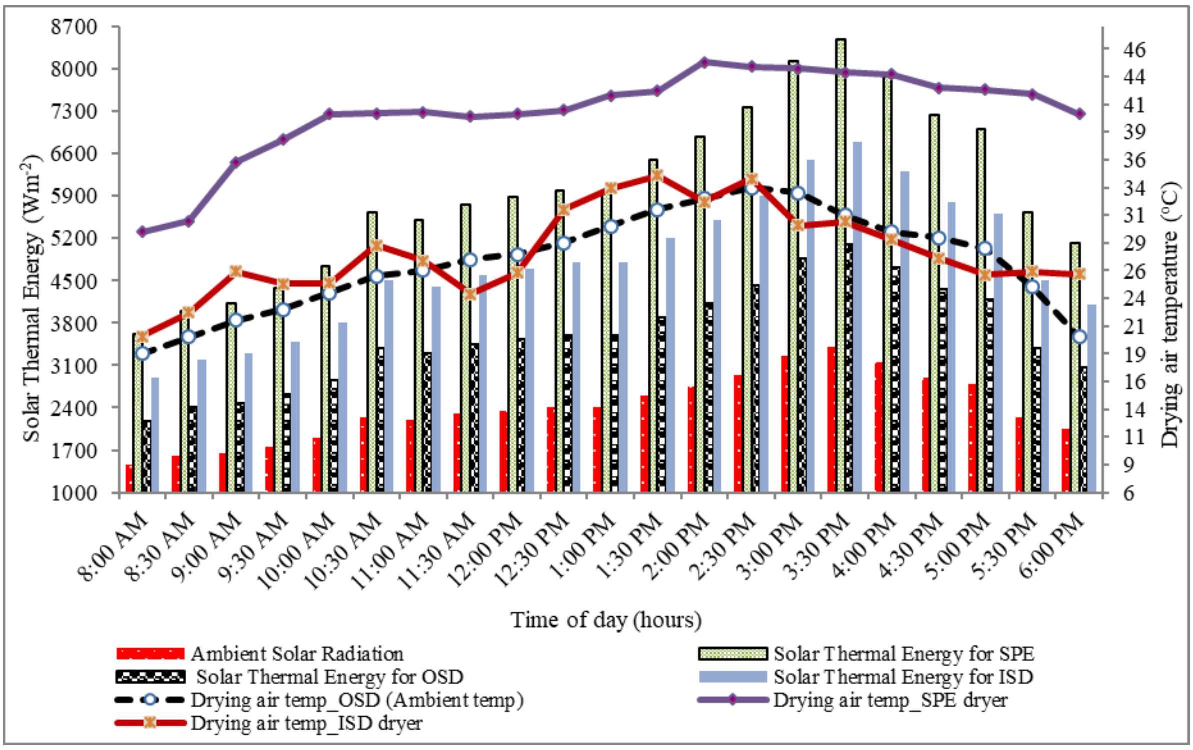

**Figure 9: Mean variation in the solar thermal energy and drying air temperatures with time for the ISD and SPE dryers and OSD methods**

Unlike the traditional OSD method, the individual ISD and SPE dryers had more stable drying air temperatures and solar thermal energy throughout the food drying cycles (Fig. 9). The solar thermal energy and drying air temperatures for the ISD and SPE dryers were also higher than that of the OSD method, suggesting better food drying conditions attained by both the ISD and SPE dryers than the traditional OSD method. However, the solar thermal energy and drying air temperatures achieved by the SPE dryer were considerably higher than those achieved by the ISD dryer. This means that, although the ISD unit was capable of raising the thermal energy and drying air temperatures above that of the OSD method, its capacity to increase both the internal energy and drying air temperatures was below that of the conventional active mode solar dryers.

Results also show that modifying the ISD concentrator plate by incorporating multiple metallic concentrators increased the internal solar thermal energy and drying air temperatures above the ambient conditions, thereby providing better drying conditions than the OSD method. Increased greenhouse warming effect was also certainly responsible for boosting both the internal thermal solar energy and drying air temperatures within the ISD cabinet. Therefore, enclosing the drying cabinet of the ISD with the greenhouse plastic film could have accelerated the greenhouse warming effect in the ISD cabinet, as was the case for the solar dryers developed by Krawczyk *et al*. (2012) and Vijayan *et al*. (2016). The increased thermal energy and drying air temperatures observed in the modified ISD prototype is consistent with the results from the solar-driven greenhouse dryers developed by Ayyappan *et al*. (2016); Chauhan and Kumar (2016), and Janjai *et al*. (2009), who also reported that the greenhouse warming effect in dryers coupled with greenhouse walling materials significantly increased in the drying air temperatures and thermal energy relative to the conventional solar dryers.

The higher drying air temperatures achieved by the individual ISD and SPE dryers than the OSD method (Fig. 9) and could also serve as a deterrent to rodents, insects, and microbial pathogens including fungi and bacteria. This could, henceforth, protect the dried product against contamination and infestations during the drying process, as was the case for the solar dryers developed by Bala and Serm (2009) and the hybrid dryers made by Bala and Janjai (2012).

The drying air temperatures achieved by the SPE dryer were between 37 and 60 $^{o}$C; which is also a matching temperature range attained by other conventional hybrid solar dryers developed by Rabha *et al*. (2017) and Wang *et al*. (2018). These dryers were also operated under active mode. But the ISD unit instead raised the internal drying air temperatures higher than that achieved by the same conventional passive-mode hybrid solar dryers developed by Alonge and Adeboye (2012); Bala and Serm (2009), and Bala and Janjai (2012). These dryers were capable of increasing the drying air temperatures above that of the ambient temperatures only from 6.4 to 9 $^{o}$C, depending on the cloud cover and related weather conditions.

For the ISD prototype, enclosing the drying chamber with a plastic greenhouse cover material could cause undesirable condensation coupled with the building up of superfluous moisture from the succulent produce during the drying process. This could cause non-uniform drying of produce and mould growth on the products. There was also a secondary possibility of attaining excessive heat fluxes and vapour pressure within the drying chamber. These challenges were solved by elongating the chimney on top of the drying chamber from 0.7 meters (the usual length as in conventional dryers) to 1.8 meters (in the ISD prototype). Elongating the chimney of the ISD served to increase suction force for removing the surplus moisture and vapour pressure within the ISD drying chamber. The excessive heat flux, vapour pressure, and moisture build-up in the dryer chamber are offset by the convective effect through the elongated chimney. Besides reading the moisture build-up, the elongated chimney was also employed to prohibit over-drying or heating of the produce by regulating the drying air temperature and thermal energy attained within the drying chamber. Thus, the temperatures and solar thermal energy for the ISD prototype were controlled and ranged from 20 to 35$^o$C and from 2900 to 6800 W/m$^2$ (Fig. 9), respectively. The optimized drying temperature-temperature variables for the pineapples and mangoes were 30.4 and 31.6$^o$C, respectively. Achieving the optimum temperatures for the ISD and SPE dryers was important to ensure consistency in the drying kinetics and quality of the dried fruit products.

However, the drying air temperatures achieved by the ISD unit were also slightly lower than the temperatures reported in the literature for a few conventional solar dryers operated under the same passive mode. For instance, the indirect passive-mode solar dryer developed by Jain and Tewari (2015) managed to raise its drying air temperatures between 40 and 45$^o$C. The drying air temperature attained by an indirect passive-mode solar dryer fabricated by Vijayan *et al*. (2016) was between 40 and 50$^o$C. Correspondingly, the indirect solar dryer constructed by Lingayat *et al*. (2017) raised the drying air temperatures in the cabinet from 44 to 55$^o$C, above that of the ambient temperatures.

On the other hand, the intensity of solar thermal energy for the three drying systems (ISD and SPE dryers, and OSD method) was consistently lower during the early morning hours from 8:30 to 11:30 AM, but it steadily increased to a peak during the afternoon hours from 12:00 to 3:00 PM. And afterwards, the solar thermal energy decreased gradually in the evening hours from 4:00 to 6:00 PM until the fruit drying experimental runs were stopped. The observations made from this study concur with the results reported from the solar drying experiments conducted by Hegde *et al*. (2015); Phadke *et al*. (2015); Bhardwaj *et al*. (2017); and Ivanova and Andonov (2001), who reported higher drying temperatures and thermal energy in the solar dryers during the afternoon hours between 11:00 AM and 3:00 PM than in the late evening hours.

### 4.2.2 The moisture content and drying rate

#### (i) Mean drying rate and moisture content of the dried mango and pineapple products

Table 5 presents the mean variation in the drying rate and moisture dehydrated from the dried pineapples and mangoes for three solar drying methods (SPE and ISD dryers and OSD method). The findings from this study indicate that the quantity of moisture dehydrated from the fruits (pineapples and mangoes) was significantly ($p<0.05$) higher in the fruits dried under the SPE dryer than those dried under the ISD dryer. Correspondingly, the quantity of moisture dehydrated from both the pineapples and mangoes was lowest in the fruits dried using the OSD method (Table 5). The aforesaid results suggest an enhanced capability of the SPE and ISD dryers in dehydrating the fresh succulent produce than the OSD method. The results further confirm the superior role of the SPE dryer in the effective drying of the fresh and succulent produce relative to the ISD dryer. The mangoes and pineapple samples dried under the traditional OSD method had the lowest moisture loss (Table 5). The abrupt changes in the ambient weather, including the humid and cloudy conditions, exposed the produce to uncontrolled temperatures coupled with the fluctuations in humidity during the OSD drying process. Therefore, the change in ambient weather conditions also compromised the drying air temperatures, solar thermal energy, and other kinetics of the fruits, thereby slowing down the drying rate and moisture loss.

**Table 5: Moisture loss and drying rate of the fruits (mangoes and pineapples)**

| Response variables | Treatment variables | SPE dryer method (n=20) | ISD dryer method (n=41) | OSD Method (n=62) |
|---|---|---|---|---|
| **Moisture content (%)** | Pineapples | $48.58 \pm 7.009^{a}$ | $44.97 \pm 4.684^{b}$ | $41.13 \pm 3.502^{c}$ |
| | Mangoes | $45.36 \pm 7.457^{a}$ | $43.09 \pm 4.775^{b}$ | $34.63 \pm 3.473^{c}$ |
| **Drying rate (g/minute)** | Pineapples | $0.135 \pm 0.0071^{a}$ | $0.079 \pm 0.0014^{b}$ | $0.060 \pm 0.0009^{c}$ |
| | Mangoes | $0.207 \pm 0.0097^{a}$ | $0.087 \pm 0.0014^{b}$ | $0.073 \pm 0.0019^{c}$ |

Values are computed arithmetic means with standard deviation (+SD) for values taken at every 30-minute interval during the drying process, n = number of readings taken during each of the 3 replicate drying cycles, and comparisons were made between the three solar drying methods. Means in the same row bearing different superscript alphabetic letters are significantly different at 5% ($p<0.05$).

All the fruits were dried to the safe storage moisture content of 10% or below, where the water activity is significantly decreased for deterioration to occur (Cherotich & Simate, 2016). The quantity of moisture dehydrated from the pineapples and mangoes dried using the SPE and ISD dryers was lower than 73.19 and 56.39% (w.b) for mangoes and pineapples, respectively; which were dehydrated using the conventional solar dryers developed by Bala and Serm (2009). On the contrary, the quantity of moisture removed from the mangoes dried using the SPE and ISD dryers was higher than 13.79% (w.b) moisture content extracted from the mangoes using dryers developed by Dissa *et al*. (2009). Goyal *et al*. (2006) and Cherotich and Simate (2016) reported moisture content removed from mangoes as 12% (d.b) and 13-14% (w.b), respectively, which was also lower than that desiccated using the ISD and SPE dryers. Likewise, the moisture dehydrated from the pineapples using the SPE and ISD dryers was higher than 25.1% (w.b) moisture content dehydrated from honey-treated pineapples reported by Abano (Abano, 2010).

Nonetheless, the quantity of moisture removed from the pineapples and mangoes dried using the SPE and ISD dryers was in total agreement with that dehydrated from the same fruits using the conventional active and passive-mode solar dryers, respectively made by Wang *et al*. (2018) and Alonge and Adeboye (2012). Wang *et al*. (2018) reported that the moisture dehydrated from pineapples dried under the passive and active mode solar dryers were and 42.6 and 47.3% (w.b), respectively. Likewise, Alonge and Adeboye (2012) reported that the moisture removed from mangoes dried using the passive and active dryers were 44.1 and 43.1% (w.b), respectively.

When comparing the drying rate of both the mangoes and pineapples between the solar drying methods, the ISD and SPE dryers displayed significantly ($p<0.05$) higher drying rates than the OSD method (Table 5). However, the drying rate exhibited by the active mode SPE dryer was significantly ($p<0.05$) higher than that of the passive-mode ISD dryer, implying that the SPE dryer is capable of drying the products faster than the ISD dryer as well as the OSD method.

Besides, the observed drying rates for both the pineapples and mangoes under the OSD method were lower than that witnessed in Ghana by Tibebu (2015), who reported drying rates of pineapple and mango as 0.258 and 0.395 g per minute, respectively, under the open sun. Equally, the drying rates of the pineapple and mango slices achieved by the modified ISD dryer were also noticeably slower than that achieved by the conventional passive, indirect solar dryer which was made by Tibebu (2015) in Ghana; whose drying rates were 0.420 and 0.307 g per minute for the pineapple and mangoes; respectively.

The observed differences in drying conditions, namely moisture content, drying air temperatures, and drying rates between the ISD and SPE dryers and the conventional solar dryers, could be partially contributed by the spatial variations in the intensity of ambient solar radiation energy and drying air temperatures between the experimental sites. For instance, the dryer made by Tibebu (2015) registered higher drying air temperatures and faster drying rates than the ISD and SPE dryers, probably due to the spatial differences in latitudinal and longitudinal site locations between East Africa and Ghana. This could also have increased the intensity and duration of the ambient solar thermal radiation. Accordingly, Ghana experiences higher radiation intensity and temperatures than that in Uganda and Tanzania, given its location in the semi-arid climatic zones as opposed to the equatorial weather conditions in East Africa (IPCC, 2014). This could have boosted the drying rate of the solar dryers constructed by Tibebu (2015).

Belessiotis and Delyannis (2011) also observed significant variations in the drying rates of fruits dried in the solar dryers and under the open sun in different areas and locations. They also further reported significant variations in the ambient temperatures and solar radiations, which translated into dissimilar drying air temperatures and solar thermal energy for the same dryers between the varied locations. It was further reported that the drying rate and air temperatures of solar-driven dryers are significantly reduced during the cloudy and rainy hours with limited solar radiation intensity and vice versa (Bhardwaj *et al*., 2017).

In summary, the observed discrepancies in the drying performance between the ISD and SPE dryers and the conventional passive and active mode dryers as reported in the literature above; could be contributed by the spatial variations in the weather conditions, particularly cloud cover, solar radiation intensity, and duration at the different food drying sites.

### (ii) Mean variation in the drying rate and moisture content between the solar drying methods

There was a continuous fluctuation in the moisture content of the pineapples during the entire drying cycles for the ISD and SPE dryers, as well as the OSD method (Fig. 10).

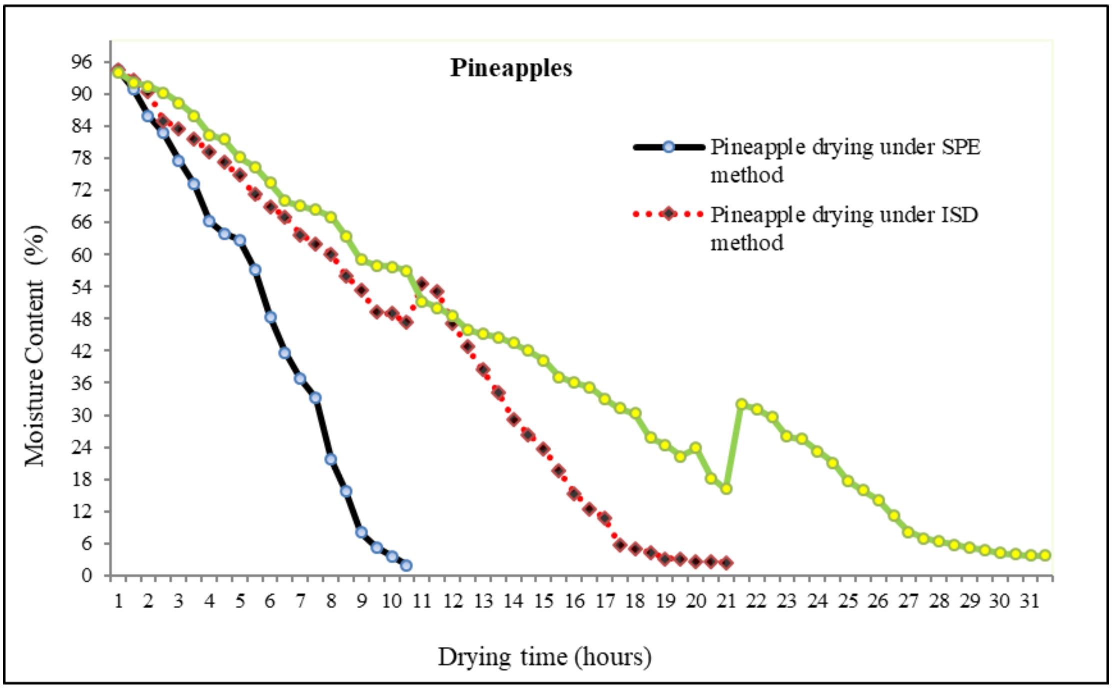

**Figure 10: Graph of variation between moisture content and drying time for the pineapples**

The moisture content of the mangoes continued to fluctuate during the drying process for the SPE and ISD dryers, as well as the OSD method (Fig. 11).

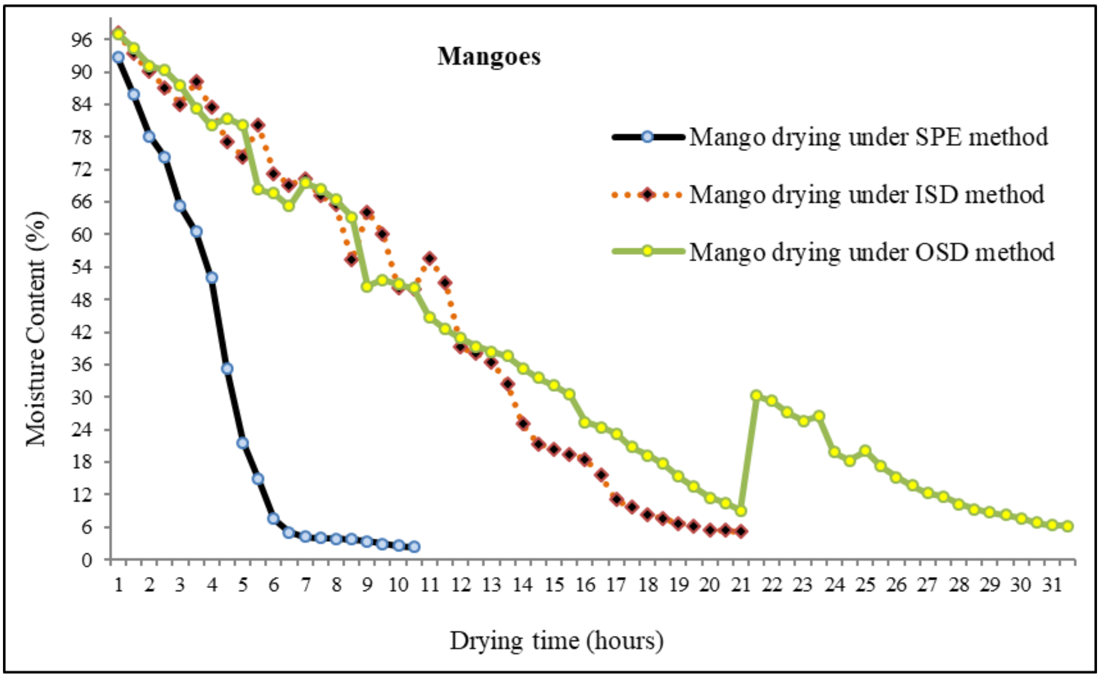

**Figure 11: Graph of variation between moisture content and drying time for the mangoes**

The SPE prototype dried the pineapple and mango cultivars in 10 hours as opposed to the 18 and 30 hours taken by the ISD dryer and the OSD method, respectively. This observation suggests that both the conventional SPE dryer and the modified ISD prototype dehydrated the pineapple and mango fruits faster than the traditional OSD method. The results have shown that the moisture content in both pineapple and mangoes consistently decreased with drying time until an optimum moisture content level was reached and maintained; which is consistent with other food drying studies reported in the literature by several solar dryers (Bhardwaj *et al*., 2017; Dalgıç *et al*., 2012; Eze & Agbo, 2011; Gürlek *et al*., 2009; Janjai, Lamlert, Intawee, Mahayothee, Boonrod, *et al*., 2009; Krawczyk *et al*., 2012).

Farmers and processors desire to use the most efficient technology to dry and process the largest quantity of their products as soon as possible. Therefore optimum drying time depends on the technology used and the standards set by the farmers and agro-processors. But in general terms, Belessiotis and Delyannis (2011);  and Mustayen *et al*. (2014) asserted that the anticipated that the average drying time for the solar-dried fruits, including mangoes and pineapples, is between 15 and 30 hours of an uninterrupted drying process. The SPE and ISD dryer, therefore, took a shorter drying duration than the time taken by the conventional active mode and passive-mode solar dryers made by Belessiotis and Delyannis (2011). These dryers took over 17 and 30 hours of constant drying to sufficiently dry the pineapple and mango slices, respectively. The shorter drying time taken by both the SPE and ISD prototypes suggests that they are capable of drying produce faster than the conventional active and passive-mode hybrid solar dryers on the market.

The drying air temperature, internal solar thermal energy and humidity are the key factors that could have determined the drying rates of the ISD and SPE dryers as well as the OSD method. The ISD and SPE dryers generated higher produce drying air temperatures within the drying cabinets than the ambient drying air temperatures under the OSD method. By increasing the temperatures of produce drying air in the cabinets of the ISD and SPE dryers, the internal thermal energy was enhanced whilst the relative humidity was reduced.

And as a result, the drying rate as a vehicle for dehydrating both mango and pineapple products was boosted for the ISD and SPE dryers, as was also the case for the solar drying experiments conducted by Phadke (2015) and Mustayen *et al*. (2014). The fruit drying results reported also collaborate the finding of Ayyappan and Mayilsamy (2010), Ayyappan and

Mayilsamy (2016), and Bolaji and Olalusi (2008), who found an enhanced food drying rate at increased drying air temperatures and a reduced humidity within the drying systems.

There was an accelerated decline in the moisture content of both pineapple and mango cultivars during the initial stages of the fruit drying process. The rate of moisture loss declined in the intermediate stages of drying and remained constant in the final drying stages under the three solar drying systems. The accelerated decline in the moisture content of both the pineapple and mango cultivars during the initial stages of drying corresponded to the higher drying rate due to relaxed desiccation of superfluous moisture from the highly succulent fruit samples (Cherotich & Simate, 2016; Dorouzi *et al*., 2018). While the decline in the moisture content from a peak in the afternoon to a constant rate during the evening hours was due to sustained stabilization of the drying air temperatures; which stabilized humidity between for the dried samples and drying air temperatures to equilibrium during the late stages of the sample drying process (Cherotich & Simate, 2016; Dorouzi *et al*., 2018).

### 4.2.3 The drying efficiency

Figure 11 shows the drying efficiency for the SPE and ISD dryers and OSD methods for both the pineapples and mangoes. The drying efficiencies for the SPE and ISD dryers were higher than the efficiency under the traditional OSD method, suggesting better fruit drying performance of the SPE and ISD dryers than the traditional OSD method. But the drying efficiency of the SPE dryer was higher than that of the ISD dryer, suggesting a superior role of the SPE dryer than the ISD unit. The difference in drying efficiency of the ISD and SPE dryers could be attributed to their distinct mode of operations as hybrid passive and active modes, respectively.

In a study conducted by Cherotich and Simate (2016) and Schiavone (2013), while assessing the performance of the conventional passive and active solar dryers, drying efficiencies of 10.8 and 33.9%, respectively, were reported. These efficiency values were significantly ($P<0.05$) lower than those obtained by the ISD and SPE dryers (Fig. 11), which were also operated under passive and active modes, respectively. It can, therefore, be inferred that the modified ISD and SPE dryers are characterized by higher drying efficiency coupled with satisfactory drying rates than the conventional solar dryers operated under passive and active modes, respectively.

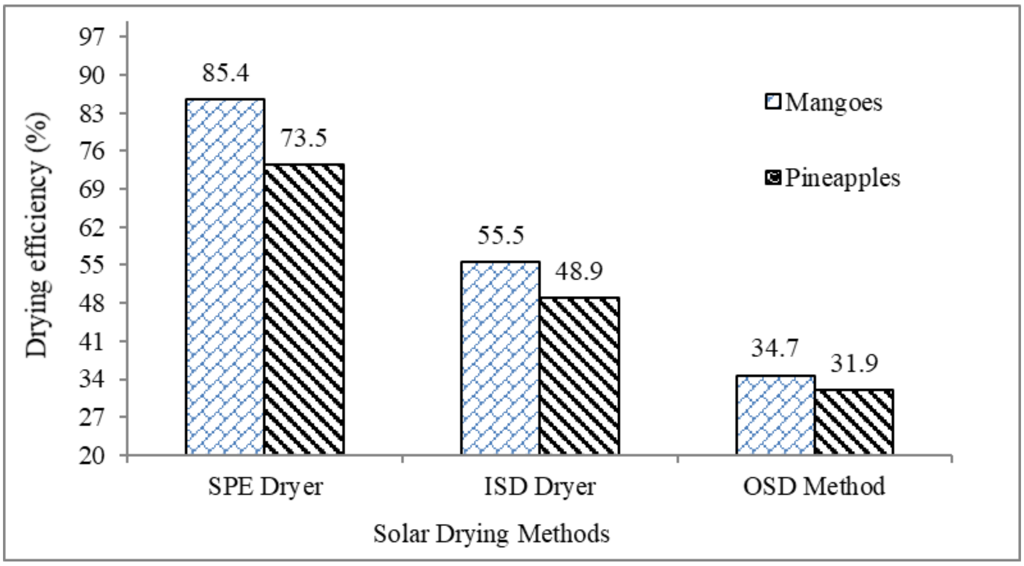

**Figure 12: Drying efficiency for the solar drying methods**

The results further suggest that modifying the solar concentrator plate of the ISD dryer by integrating multiple cylindrical metallic concentrators coupled with enclosing the ISD drying cabinet with the greenhouse plastic materials increases the relative drying efficiency of the ISD system more than twice that achieved by the OSD method.

The relative drying efficiency of the conventional SPE and improved ISD dryers was higher than the efficiency of the conventional active and passive-mode solar dryers reported in the following literature. Thus, the drying efficiencies reported for the active mode dryers were; 33.8% for drying mangoes under the conventional passive-mode solar dryer unit, which was developed by Wang *et al*. (2018); whereas the efficiency of 8.5% was attained in drying ginger using indirect forced convection solar dryer made by Rabha *et al*. (2017). Similarly, the food drying efficiencies reported for the passive mode solar dryers were; 28.2% in drying mint leaves from the indirect passive natural convective solar dryer made by Jain and Tewari (2015); 19% was achieved in drying bitter gourd from a sensible storage indirect passive dryer made by Vijayan *et al*. (2016) and; 22.38% and 4.05% were recorded under indirect solar dryer when drying banana and ghost chilli pepper, respectively for the dryer units developed by Lingayat *et al*. (2017).

The above observations suggest that modifying the solar collector plate with multiple metallic concentrators coupled with enclosing its drying cabinet with a specialized greenhouse cover material, as was the case for the modified ISD unit, increases the drying efficiency of the solar drying systems beyond that of the conventional passive-mode solar dryers.

However, the observed variations in the drying performance of the ISD and SPE dryers relative to that of conventional passive and active mode solar dryers reported in the literature could also be explained by the differences in structural modifications in the designs as well as the composition and quality of material used in making the dryers. This conclusion collaborates the results from numerous fruit drying studies using solar dryers developed by Dorouzi *et al*. (2018); Belessiotis and Delyannis (2011); Tibebu (2015); Vijayan *et al*. (2016); Wang *et al*. (2018); and Wankhade *et al*. (2013); who reported higher drying performance mainly in terms of drying air temperatures, drying rate and efficiency in the solar dryers with modified designs.

Tibebu (2015) and Wankhade *et al*. (2013) also reported that the solar dryers that were fabricated using better designs and quality materials registered higher performance than the conventional dryers, which were developed using low-quality materials. This is because improving the design configurations of the physical dryers and also using high-quality materials during fabrication of the dryers is proven to increase the quantity of solar thermal energy collected, stored and used in drying (Hii *et al*., 2012). Several studies also confirm that modifications in the designs of the solar dryers improved the drying rate and drying efficiency as well as other related performance factors (Bhardwaj *et al*., 2017; Bolaji & Olalusi, 2008; Chua & Chou, 2003; Krawczyk *et al*., 2012; Leon *et al*., 2002; Navale *et al*., 2015; Wankhade *et al*., 2013).

## 4.3 The effect of the individual solar dryers and the open sun drying method on the sensory quality attributes and the nutritional content of the dried products

In this study, the effect of using the three solar drying methods (thus ISD and SPE dryers, and OSD methods) on the sensory quality attributes and nutritional content of the dried fruit products was assessed, using mango and pineapples as the case study.

### 4.3.1 Effect of the solar dryers and the open sun drying method on the sensory quality attributes

In assessing the effectiveness of using the ISD and SPE dryers, and OSD methods on the sensory quality attributes of the dried fruit (mango and pineapple) products, the following sensory parameters were considered; taste, aroma, colour, and general acceptability of the dried products.

Figure 13 presents the mean scores of sensory parameters from the panel of 15 consumers, who evaluated the dried mango and pineapple products, which were dried using the ISD and SPE dryers, and OSD methods.

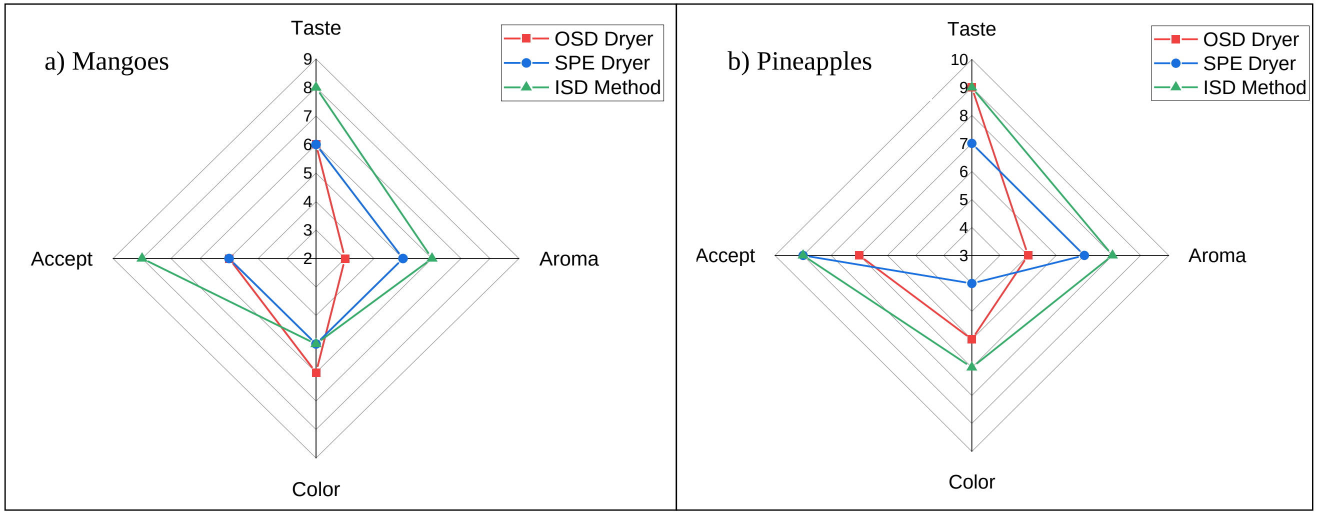

**Figure 13: A radar chart showing the mean scores for the sensory attributes of fruits: Mangoes (a) and Pineapples (b)**

The evaluated sensory attributes varied considerably between the solar drying methods for both mangoes and pineapple products. The mean rank of the desirable sensory attributes for the dried mango and pineapple slice products ranged from 4 (dislike slightly) to 9 (like extremely). The results suggest that the consumers generally liked both the dried pineapple and mango products, irrespective of the solar drying method used. The mean scores for the taste, aroma, and colour of the mango products dried using the ISD and SPE dryers were higher than the scores given for the fruit products dried using the OSD method (Fig. 13). The sensory attributes were ranked highest in the mango and pineapple products dried under the ISD method followed by the SPE dryer and were lowest for the products dried under the OSD method suggesting higher consumer acceptability of the fruit products dried using the ISD dryer. However, relative to the sensory quality attributes of the solar-dried fruits (mango and pineapple), products were considered acceptable (Fig. 13).

The sensory quality attributes were retained in the solar-dried mangoes and pineapple products, and the products were generally accepted by the panel of consumers. The results collaborate with the findings of CalínSánchez *et al*. (2013), who reported that solar drying technology involving the use of improved and modern drying technologies significantly improved the sensory properties of the pomegranate fruits. Similarly, Elias *et al.* (2008) further observed and reported that the solar drying process improved the taste and texture of the persimmons fruits and consequently also influenced over 80% of consumer acceptability of the solar-dried fruits (persimmons).

However, the panellists were from diverse social settings and had limited exposure to the solar-dried fruits, particularly the dried mango slices, which could have also influenced their perception and assessed the overall acceptability of the dried mangoes as ‘dislike slightly. The results are also in total agreement with the findings reported by Owureku-Asare *et al.* (2017), who identified three demographic factors, namely, the knowledge, exposure, and the perceived quality of the dried food products as the leading factors influencing both the consumer preference and acceptability of the dried fruits.

The higher organoleptic quality of the mangoes and pineapples dried under the ISD and SPE dryers than those dried using the OSD method was probably contributed by better drying conditions, mainly drying rate and uniformity. The transition from the traditional open sun drying methods to the direct, indirect, hybrid, and modified hybrid solar dryers gradually increases the food drying air temperatures, thermal energy, and efficiency (Hii *et al.*, 2012;

Kumar *et al.*, 2016; Orphanides *et al.*, 2016). This could have, consequently, resulted in enhanced retention of the organoleptic quality of the fruit slices dried in the ISD and SPE dryers than the traditional OSD method.

### 4.3.2 Effect of using the solar dryers and open sun drying method on the nutritional content and chemical composition

The effect of using the ISD and SPE dryers and OSD methods on the nutritional content and chemical composition of the dried fruit (mango and pineapple) products; and the fresh fruits (that also provided the baseline parameters) was evaluated. The nutritional content and chemical composition parameters investigated were moisture content, dry matter, total carbohydrates, total titratable acidity, phenols, total sugar content, mineral content, vitamin C and beta carotene content.

#### (i) Variation in concentration of the chemical parameters

Table 6 presents the variations in the concentration of chemical parameters, namely; moisture content, dry matter content; carbohydrates; total acidity; and total phenols both in the fresh and dried fruits (mango and pineapple) products. There were highly significant ($p<0.05$) variations in the concentration of chemical parameters both in the mango and pineapple products dried using the ISD and SPE dryers and the OSD method (Table 6).

**Table 6: Variations in the concentration of chemical parameters between the fresh and dried fruit (mangoes and pineapples) products using different solar drying methods**

| Chemical parameters | Fresh fruits (Control) | OSD Method (Traditional) | SPE Method (Active mode) | ISD Method (Passive mode) |
|---|---|---|---|---|
| **Mangoes** | | | | |
| **Moisture content (g/100g)** | 89.73±1.12$^{a}$ | 84.55±1.75$^{b}$ | 89.43±1.78$^{c}$ | 87.21±1.78$^{d}$ |
| **Dry matter content (%)** | 24.74±0.3$^{a}$ | 27.6± 1.2$^{b}$ | 29.7±1.5$^{c}$ | 34.5±1.6$^{d}$ |
| **Carbohydrates (mg/L)** | 10.6±0.5$^{a}$ | 11.7±0.6$^{b}$ | 14.9±0.4$^{c}$ | 16.5±0.5$^{d}$ |
| **Total acidity (%)** | 0.53±0.02$^{a}$ | 0.47±0.05$^{b}$ | 0.32±0.03$^{c}$ | 0.24±0.03$^{d}$ |
| **Total Phenols (mg/L GAE)** | 0.85±0.02$^{a}$ | 0.44±0.06$^{b}$ | 0.72±0.03$^{c}$ | 0.75±0.03$^{c}$ |
| **Pineapples** | | | | |
| **Moisture content (g/100g)** | 43.75±0.72$^{a}$ | 45.85±1.01$^{b}$ | 48.98+1.13$^{c}$ 25.8±0.3$^{c}$ | 47.42+1.11$^{d}$ 26.9±0.3$^{d}$ |
| **Dry matter content (%)** | 18.47±0.1$^{a}$ | 23.6±0.5$^{b}$ | | |
| **Carbohydrates (mg/L)** | 23.3±0.2$^{a}$ | 24.4±0.3$^{b}$ | 26.8±0.5$^{c}$ | 27.9±0.6$^{d}$ |
| **Total acidity (%)** | 3.4±0.01$^{a}$ | 2.9±0.01$^{b}$ | 2.3±0.02$^{c}$ | 1.8±0.02$^{d}$ |
| **Total Phenols (mg/L GAE)** | 0.43±0.02$^{a}$ | 0.30±0.04$^{b}$ | 0.39±0.02$^{c}$ | 0.41±0.03$^{b}$ |

Values are the arithmetic means of measurements taken from three replicate fruit samples, with their corresponding standard errors (SE). The values of the chemical parameters for the solar drying methods (ISD and SPE dryers, and OSD) within the same row followed by different alphabetical letters were significantly different at 5% ($p<0.05$) level.

The quantity of moisture removed from the mangoes and pineapples significantly ($p<0.05$) varied between the drying methods and was highest in the slice sample products dried using the SPE dryer, followed by the ISD and was lowest for the OSD method. Relative to the baseline parameters of the fresh fruits, there was a significant ($p<0.05$) increase in the concentration of the dry matter content and carbohydrates in the dried fruit (mango and pineapple) products.

The increase in the concentration of dry matter content and carbohydrates was pronounced in the fruit slice samples dried using the ISD dryer, followed by the SPE dryer, and was lowest in the fruit products dried under the traditional OSD method. The reduction in the total phenolic content was highest in the fruit slice samples dried using the OSD method, followed by the SPE dryers and was lowest in the products dried using the ISD method. The results suggest that the ISD dryer is exclusively capable of retaining more dry matter content, carbohydrates and total phenolic content in the dried fruits (mango and pineapple) products than the SPE dryer and the traditional OSD method.

Conversely, there was a significant ($p<0.05$) increase in acidity of the solar-dried products, and the increase was highest and lowest in the fruit products dried using the ISD and OSD methods, respectively. All the chemical composition parameters for the mangoes and pineapples dried using the ISD dryer were significantly ($p<0.05$) higher than the SPE method, further suggesting both the upgraded capacity and superior role of the ISD in retaining the chemical composition of the dried fruit products.

The solar drying (ISD and SPE dryers, and OSD method) process caused a significant increase in concentrations of the chemical parameters except for the acidity and the total phenolic content in the dried products, and the increase could be associated with the solar drying process. This was so because all the solar drying processes, irrespective of the modification or operation mode, cause considerable changes in the biological, physical and chemical composition of different fruit products, including mangoes and pineapples (Babu *et al*., 2018; Hii *et al*., 2012; Kumar *et al*., 2016; Orphanides *et al*., 2016; Prakash *et al*., 2016).

Besides the difference in the drying methods, the increase in acidity could also be explained by the fact that both the pineapple and mango fruits were ripe with probably higher concentrations of citric and malic acids. The concentrations of both citric and malic acids in fruits increase with ripening, and they constitute the main organic acid content (Etienne *et al*., 2013). The additional reduction in total acidity in the mango and pineapple slice sample products dried using the ISD and SPE dryers than the slices dried under the OSD method could be explained by the increase in concentrations of total organic acid content following accelerated dehydration. Hii *et al*. (2009) also found a positive correlation relationship between the total acidity content and organic acid content in fruits dried at higher temperatures over a short duration than those dried at the reduced temperature over a longer duration. The slow drying process, mainly under the OSD methods, could have increased biodegradation and evaporation of excessive organic acids from the dried fruit (mango and pineapple) products than the rapid drying processes; as it was also the case for the cocoa products dried by Hii *et al*. (2009), and mango powders processed by Caparino *et al*. (2012).

The relatively higher retention of the chemical content in the fruits dried under the SPE and ISD dryers than the fruit products dried under the traditional OSD method could have probably increased temperatures and reduced drying times which have probably accelerated the fruit drying process. For instance, the increase in total acidity, carbohydrates, and total sugars was probably caused by enhanced dehydration that led to the excessive moisture removal from the fruits, and this could have amplified the concentration effect of the aforesaid chemical nutrients (Abrol *et al*., 2014). Similarly, Abrol *et al*. (Abrol *et al*., 2014) further attributed the increase in total acidity of the dried fruits to the development of additional acids from the inter-conversion of soluble and related biochemical reactions of sugars.

Some phenols, including esters, have an aromatic ring with hydroxyl-substituents and are highly vulnerable to thermal and oxidative degradation (Grajek & Anna, 2010; Ouyang et al., 2018). Therefore, substantial quantities of the phenols could have been lost from the mango and pineapple fruits during the preparation processes of peeling and slicing because the fruits were directly exposed to oxygen. This assertion is consistent with the findings of Grajek and Anna (2010) and Ouyang *et al*. (2018), who too reported a high loss of phenols from the fruits due to increased oxidative degradation under oxygen during the peeling process.

On the other hand, the additional loss of the total phenolic content from the mango and pineapple products dried under the OSD method than the fruit products dried under the SPE and ISD methods could have been caused by the prolonged drying process exhibited by the OSD method. The results suggest that all the solar drying methods caused a significant decline in the total phenolic content of the dried fruits (mangoes and pineapples) products.

The results are consistent with the total phenolic content found in *Salvia officinalis* products by Hamrouni-Sellami *et al*. (2013) and in tomatoes by Chang *et al*. (2006). They reported that different types of solar drying processes, including the open sun drying, microwave, and oven drying methods, caused significant reductions in the total phenolic content in the dried fruit (*Salvia officinalis* and tomato) products. The decline in the total phenolic content of the dried mango and pineapple slice products could have also been caused by thermal degradation of the phenolic content; as it was the case for the fruit and vegetable products dried by Suvarnakuta *et al*. (2011) and Ouyang *et al*. (2018).

Similar reductions in the phenolic content of the dried fruits and vegetables were observed in the ginger leaves reported by Chan *et al*. (2009); in the olive mill, as reported by Obied *et al*. (2008); in persimmons reported by Park *et al*.(2006); in apricots reported by Madrau *et al*. (2009); in mulberry leaves reported by Katsube *et al*. (2009); and also in prune reported by Del Caro *et al*. (2004).

Additional reduction in the total phenolic content occurred in both the mango and pineapple slice sample products dried under the traditional OSD method than the products dried using the ISD and SPE dryers. The additional loss of total phenolic content in the fruit products dried under the OSD method could have been attributed to the prolonged drying process. This was so because the prolonged fruit drying process causes additional loss of volatile nutrients from the dried fruits (Abrol *et al*., 2014). The results also collaborate the nutritional loss results in *Zingiber officinale Roscoe* observed by An *et al*. (2016); and in several fruits, including mangoes and pineapples observed by Ouyang *et al*. (2018). They also reported significant reductions in the total phenolic content of fruits dried when subjected to prolonged drying duration, irrespective of the method of drying used.

### (ii) Variation in concentration of the nutritional content parameters

Table 7 presents the variations in the concentration of the nutritional content, namely total sugar profiles, mineral content, and the composition of vitamins A and C, both in the fresh and dried fruit (mango and pineapple) products. Relative to the baseline nutritional content in the fresh mango and pineapple samples, the solar drying methods (thus ISD and SPE dryers, and OSD method) caused a significant ($p<0.05$) increase in the concentration of the total sugars and mineral content in the dried products. The total sugars and mineral content was higher in the fruit products dried using the SPE and ISD dryers than in the products dried using the traditional OSD method. The increase in the concentration of the minerals and total sugars was significantly ($p<0.05$) higher in the fruit products dried using the ISD dryer than the SPE dryer (Table 7), which further confirmed the superior role and enhanced capacity of the ISD system in retaining the nutritional content of fruits during the solar drying process.

**Table 7: Mineral and vitamin content of the mango and pineapples dried under the three solar drying methods at Nelson Mandela African Institution of Science and Technology, Tanzania**

| Nutritional Content parameters | Fresh fruits (Control) | OSD Method (Traditional) | SPE Method (Active mode) | ISD Method (Passive mode) |
|---|---|---|---|---|
| **Mangoes** | | | | |
| **Total sugars (mg/L)** | 9.1±0.3$^{a}$ | 9.2±0.4$^{b}$ | 11.2±0.6$^{c}$ | 14.3±0.3$^{d}$ |
| **Calcium (mg/L)** | 8.48±0.11$^{a}$ | 9.61±0.12$^{b}$ | 11.61±0.13$^{c}$ | 13.22±0.14$^{d}$ |
| **Phosphorus (mg/L)** | 6.01±0.11$^{a}$ | 6.52±0.12$^{b}$ | 7.35±0.13$^{c}$ | 7.99±0.14$^{d}$ |
| **Iron (mg/L)** | 0.015±0.005$^{a}$ | 0.053±0.008$^{b}$ | 0.076±0.010$^{c}$ | 0.083±0.011$^{d}$ |
| **Manganese (mg/L)** | 0.008±0.001 | 0.013±0.005$^{b}$ | 0.026±0.004$^{b}$ | 0.032±0.005$^{b}$ |
| **Zinc (mg/L)** | 0.110±0.002$^{a}$ | 0.133±0.004$^{b}$ | 0.143±0.007$^{c}$ | 0.162±0.006$^{d}$ |
| **Copper (mg/L)** | 0.022±0.005$^{a}$ | 0.026±0.002$^{b}$ | 0.034±0.004$^{c}$ | 0.039±0.004$^{c}$ |
| **Vitamin C (mg/100g)** | 36.4±0.3$^{a}$ | 27.5±0.4$^{b}$ | 33.5±0.5$^{c}$ | 35.6±0.4$^{a}$ |
| **Vitamin A (mg/100mL)** | 851±3$^{a}$ | 820±4$^{b}$ | 836±4$^{c}$ | 849±6$^{a}$ |
| **Pineapples** | | | | |
| **Total sugar (mg/L)** | 15.7± 0.1$^{a}$ | 16.8± 0.3$^{b}$ | 21.9± 0.3$^{c}$ | 24.2± 0.3$^{d}$ |
| **Calcium (mg/L)** | 4.31±0.13$^{a}$ | 5.21±0.14$^{b}$ | 6.81±0.16$^{c}$ | 8.02±0.15$^{d}$ |
| **Phosphorus (mg/L)** | 4.03±0.13$^{a}$ | 4.73±0.11$^{b}$ | 5.25±0.14$^{c}$ | 6.49±0.14$^{d}$ |
| **Iron (mg/L)** | 0.145±0.003$^{a}$ | 0.491±0.002$^{b}$ | 0.523±0.004$^{c}$ | 0.591±0.006$^{d}$ |
| **Manganese (mg/L)** | 1.15±0.03$^{a}$ | 1.52±0.02$^{b}$ | 1.98±0.05$^{c}$ | 2.31±0.06$^{d}$ |
| **Zinc (mg/L)** | 0.051±0.002$^{a}$ | 0.059±0.004$^{b}$ | 0.763±0.003$^{c}$ | 0.837±0.005$^{c}$ |
| **Copper (mg/L)** | 0.124±0.003$^{b}$ | 0.127±0.002$^{b}$ | 0.347±0.003$^{c}$ | 0.392±0.003$^{d}$ |
| **Vitamin C (mg/100g)** | 23.4±0.2$^{a}$ | 17.8±0.2$^{b}$ | 19.9±0.3$^{c}$ | 22.1±0.2$^{a}$ |
| **Vitamin A (mg/100mL)** | 11.8±0.4$^{a}$ | 8.8±0.5$^{b}$ | 10.5±0.7$^{a}$ | 11.6±0.8$^{a}$ |

Values are the arithmetic means of measurements taken from three replicate fruit samples, with their corresponding standard errors (SE). The values of the nutritional parameters for the solar drying methods (ISD and ISD dryers, and OSD method) within the same row followed by different alphabetical letters were significantly different at 5% ($p<0.05$) level.

The increase in the concentration of the total sugars, macro and micro mineral elements in the solar-dried fruits (mangoes and pineapples) products could be linked to excessive dehydration process coupled with the ultimate substantial increase in the dry matter content of the solar-dried fruits. The increase in the concentration of the mineral content of the pineapple and mango products dried using the ISD and SPE dryers and OSD methods collaborated the results reported in the literature from several studies, including apples by Lowor and Agyente-Badu (2009); amaranthus by Mepba *et al*. (2007); and vegetables by Iqbal *et al*. (2006).

The high dehydration of the mangoes and pineapples to moisture levels of below 10 % in all the solar drying methods (ISD and SPE dryers, and OSD method) was probably the main cause of a substantial increase in the concentration of the minerals and total sugar content. This was so because a reduction in the moisture content of any succulent agro-produce causes shrinkage and increases the concentration of the non-volatile matter, including dry matter content, total sugars, macro, and micro mineral contents; due to accelerated and enriched concentration-effect during and after the drying process respectively (Abrol *et al*., 2014). The results are consistent with the findings of Suna *et al.* (2014), who reported strong positive correlation relationships between the dry matter, mineral elements, and the moisture content in the different types of fruits during and after drying.

All the solar drying methods (thus ISD and SPE dryers, and OSD method) caused significant ($p<0.05$) reductions in the concentration of the vitamins A and C in the dried mango and pineapple products except for the ISD. The loss of vitamins A and C in the mangoes and pineapples was less pronounced in the fruit products dried under the traditional OSD method than those dried using the ISD and SPE dryers. Likewise, the loss of vitamins A and C was lower in the fruit products dried using the ISD dryer than in the fruit products dried using the SPE dryer. The results, therefore, propose better suitability of the ISD dryer in retaining the volatile vitamins than both the SPE dryer and the traditional OSD method.

The OSD method caused the highest loss of vitamins A and C from the dried fruit products, and this was probably caused by full exposure of the fruits to uncontrolled ultraviolet solar thermal radiations during the OSD drying process. The vitamins, particularly vitamins A and C in fruit and other food products, are highly vulnerable to the direct UV thermal radiations from the sun; which cause oxidative damage, especially in the presence of moisture (for the fresh produce), metal ions, and sunlight (George *et al*., 2015; Li *et al*., 2017). This is so because direct UV radiations from the sun stimulate the β-carotene oxidation process (George et al., 2015); and this could have probably caused enormous loss of vitamins A and C in the fruit products (mango and pineapple) dried under the traditional OSD method. The pineapples and mangoes dried under the traditional OSD method were slowly dehydrated, and as such, they retained higher (above 16%) moisture content for a long during the lengthy OSD drying process.

On the contrary, the fruit samples dried using the ISD and SPE dryers were speedily dehydrated to a moisture content level of 15% or lower between the first 8 to 14 hours of the drying process. Retention of higher moisture content levels during the prolonged drying process could have also increased the loss of vitamins from the fruits dried using the traditional OSD method. This was so because sustaining the moisture content level of the fresh agro-produce, including fruits, at 15% and above during the prolonged drying process catalyzes key enzymatic reactions as well as other related biochemical processes (Abrol *et al*., 2014; Grajek & Anna, 2010). This was the case when drying both mango and pineapple samples under the traditional OSD method and could have also increased the loss of vitamins from the fruit products.

The traditional OSD method was highly susceptible to ultraviolet thermal radiation from the sun. And as a result, the volatile nutrient contents, including the vitamins A and C, total phenolic content, micro and macromineral elements in the products dried under the OSD method, were compromised. The observed reductions in the concentration of vitamin C between the ISD and SPE dryers and OSD methods could be caused by the difference in drying air temperatures. The high temperatures in the SPE and ISD dryers could have inactivated the ascorbic acid oxidase enzyme, which offered relative resistance against oxidation, as was the case for drying studies conducted by Leong and Oey (2012). Similar studies have also reported a reduction in the loss of vitamin C with increasing drying air temperatures; as was the case in broccoli dried by Munyaka *et al*. (2010); in cowpeas dried by Wawire *et al*. (2011), and in tomato dried by Leong and Oey (2012).

Conversely, the reduction in the concentration of vitamins A and C was more pronounced in the fruit (mango and pineapple) products dried under the OSD method than in the ISD and SPE dryers. The results are consistent with the findings of Dehnad *et al*. (2016) and Prakash *et al*. (2016), who observed and reported that the open sun drying process reduces the sensory and nutritional quality of the dried food products, particularly in fruits. The substantial loss of nutrients in the dried mango and pineapple products could have occurred during the drying process through the biochemical processes, including; caramelisation, enzymatic, and oxidation processes (Sagar *et al*., 2010; Salunkhe *et al*., 1991). The results are also in agreement with the observations made by Santos and Silva (2008), who reported that the longer the food drying process at a lower temperature, as was the case for the IOSD method, the more the loss of ascorbic acid content from the dried food products.

On the contrary, the drying cabinets of the SPE and ISD dryers were covered with plastic and UV-treated greenhouse cover materials, respectively. The cabinet plastic and greenhouse cover materials for the SPE and ISD have the ability to partially and fully protect the produce from the UV radiations, respectively. The greenhouse materials enclosing the drying cabinet of the ISD dryer increased the internal temperatures of the drying air through the greenhouse effect, as was the case for the dryer made by Chauhan and Kumar (2016).

Besides screening out the UV solar thermal radiations, enclosing the drying cabinets of the SPE and ISD dryers with the plastic and greenhouse materials also increased the internal drying air temperatures in the dryer cabinets. This could have also accelerated the fruit drying process and consequently enhanced concentration and retention of the sensory quality attributes as well as the chemical content and nutrient composition in the dried fruit products.

### (iii) Reference data for sensory valuation

Table 8 shows reference data for the sensory evaluation, as well as the standard data (for control - fresh fruits) for both mangoes and pineapples.

**Table 8: Reference and standard data for sensory evaluation of the mangoes and pineapples**

| **Fruit type** | **Solar dryer type** | **Sensory profile and quality parameters** | | | | **Hedonic scale Reference** |
|---|---|---|---|---|---|---|
| **Mangoes** | Solar dryer type | Taste | Aroma | Colour | Acceptability | 1 = Dislike extremely, |
| | OSD methods | 6.1±0.2$^a$ | 3.1±0.1$^a$ | 6.1±0.2$^a$ | 5.4±0.2$^a$ | 2 =Dislike very much, |
| | SPE prototype | 6.3±0.3$^b$ | 5.2±0.2$^b$ | 5.3±0.1$^b$ | 5.2±0.3$^b$ | 3 = Dislike moderately, |
| | ISD prototype | 8.1±0.2$^c$ | 6.1±0.3$^c$ | 5.4±0.4$^c$ | 8.1±0.2$^c$ | 4 =Dislike slightly, |
| **Preference for control (Standard)** | | 9.0±0.0 | 7.0±0.0 | 8.0±0.0 | 9.0±0.0 | 5 = Neither like nor dislike |
| **Pineapples** | OSD methods | 8.1±0.2$^a$ | 5.3±0.3$^a$ | 6.2±0.1$^a$ | 7.5±0.2$^a$ | 6 = Like slightly, |
| | SPE prototype | 7.3±0.1$^b$ | 7.1±0.2$^b$ | 4.4±0.2$^b$ | 8.1±0.3$^a$ | 7 = Like moderately, |
| | ISD prototype | 8.1±0.2$^c$ | 8.4±0.3$^c$ | 7.1±0.2$^c$ | 8.4±0.2$^c$ | 8 = Like very much, and |
| **Preference for control (Standard)** | | 9.0±0.0 | 9.0±0.0 | 8.0±0.0 | 9.0±0.0 | 9 = Like extremely. |

Values are represented as mean measurements taken from twenty replicates of the independent sensory evaluators (n =20). Different letters in the same row indicate significant statistical differences at 5% (Tukey's HSD, $p \leq 0.05$). Reference standard data for mangoes and pineapples from FAO Database (FAO, 2017).

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

A modified passive-mode solar dryer dubbed an ‘improved solar dryer (ISD)’ prototype was fabricated. The ISD unit consisted of a modified solar collector plate with multiple cylindrical metallic solar concentrators. The drying cabinet of the ISD unit is enclosed with specialized UV-treated greenhouse plastic materials. The ISD unit was proposed against the traditional open sun drying (OSD) method for drying fresh fruits. An active mode hybrid solar dryer, which uses a solar photovoltaic system with an electric backup device (SPE) dryer, was also fabricated.

The food drying performance of the active mode SPE dryer was better than that of the passive-mode ISD dryer. The SPE technology is, therefore, more suitable for drying fresh produce than the ISD dryer. However, both the SPE and ISD dryers exhibited superior drying performance and drying kinetics than the traditional OSD method. The sensory quality attributes of the dried mangoes and pineapples were maintained in all three drying methods. The dried mango and pineapple products were generally acceptable to the panel of consumers. The highest nutritional content was retained in the mangoes and pineapples products dried under the passive-mode ISD method followed by the active mode SPE dryer. Similarly, the mangoes and pineapple products dried under the traditional OSD method retained the lowest nutritional content.

Henceforth, modifying the solar collector plate of passive mode hybrid solar dryers with multiple metallic solar concentrators and putting the UV greenhouse plastic walling materials on the ISD dryer cabinet serves to boost the drying performance beyond that of the traditional OSD method. In this context, therefore, the proposed ISD technology could serve to improve the performance of drying processes as well as maintain both the sensory quality attributes and nutritional content of the dried fruit products.

## 5.2 Recommendations

### 5.2.1 Application of the improved passive-mode Improved Solar Dryer

For the novel passive-mode hybrid ISD dryer, the produce drying cabinet has four drying trays, and each has a surface area of one square meter. When operated at full capacity, each tray effectively takes 3 and 4 kg of fresh mangoes and pineapples, respectively, for drying at the same time. This means that the ISD prototype can separately dry a total of 12 and 16 kg of mangoes and pineapples, respectively, in one drying cycle. The drying performance of the ISD unit depends on the prevailing weather conditions. Under the ambient weather conditions of East Africa, the mean temperatures and solar radiations are reported to be 26.8$^{o}$C and 2398 W/m$^{2}$, respectively. Based on the performance of the ISD, the new ISD sustaining its internal drying air temperatures and solar thermal energy to an average magnitude of 28 $^{o}$C and 4795 W/m$^{2,}$ respectively. The increase in internal temperatures and thermal energy is sufficient to advance the drying performance and drying kinetics of the fruits as opposed to the traditional OSD method. With the ISD unit, the farmers have the opportunity to use the free and abundant sunshine to dry produce effectively. The ISD can dry a total of 12 and 16 kg of fresh mangoes and pineapples, respectively, just in one drying cycle, which often takes 1-2 days.

In this context, a farmer with 1.2 tons (1200 kg) of fresh mangoes requires 10 ISD dryer units to process all the products within 8-10 days effectively. With the 10 ISD units, the same farmer can process at least 3.6 tons of mangoes in a month. On the other hand, it will take a horticultural farmer, who also has 10 ISD dryers, 8-10 days, to efficiently process about 1.6 tons (1600 kg) of the fresh pineapples. Nonetheless, the ISD solely depends on the ambient solar radiation energy, which is renewable, free, and is available in abundance even in remote areas without electricity. Based on the above-mentioned contextual analysis, the ISD dryer is highly recommended for subsistence farmers and small-scale agro-processors with a few tons of fresh fruit produce for drying.

### 5.2.2 Application of the active mode Solar Photovoltaic and Electric dryer

For the active mode hybrid SPE dryer, the produce drying cabinet has six drying trays, and each has a surface area of one square meter. When operated at full capacity, each tray effectively takes 3 and 4 kg of fresh mangoes and pineapples, respectively, for drying at the same time. This means that the SPE can separately dry a total of 12 and 16 kg of mangoes and pineapples, respectively, in one drying cycle. The drying performance of the SPE unit depends on external energy sources, either from the batteries powered by the solar panels or electricity from the AC sources. Unlike the ISD, the SPE dryer is independent of the ambient weather conditions, and farmers can dry their produce indefinitely, including nights shifts or during rainy and cloudy weather conditions without direct sunshine.

Based on the performance of the SPE dryer, the SPE is capable of maintaining its internal drying air temperatures and solar thermal energy to an average magnitude of 40.3 $^{o}$C and 5994 W/m$^{2}$, respectively. The unprecedented increase in temperatures and thermal energy gives the active mode SPE unit an exclusive capacity to boost its drying performance and drying kinetics beyond that of the SPE dryer.  Based on the performance data, farmers and processors with one SPE unit have the opportunity to effectively dry a total of 12 and 16 kg of mangoes and pineapples, respectively, per drying cycle, which takes just 6-10 hours depending on the pre-set conditions.

In this context, a farmer with 1.2 tons (1200 kg) of fresh mangoes requires only one SPE dryer to effectively dry and process all the fresh produce within 3-5 days (night shifts inclusive). This means that one unit of the SPE dryer is enough for the same farmer to process at least 3.6 tons of mangoes in a month. Correspondingly, it will also take the farmers the same time to dry nearly equal quantities of the pineapple products. Based on the aforesaid contextual analysis, the SPE dryer is highly recommended for commercial farmers and large-scale agro-processors with bulk quantities of fresh produce for drying, process, and marketing.  I highly recommend the SPE dryer because it performs better than the ISD dryer with higher drying efficiency. The drying process of the SPE dryer is independent of the ambient weather conditions, meaning that it can be operated indefinitely, even during night shifts and rainy days without direct sunshine.

### 5.2.3 Recommendations for future studies

Due to the financial and other logistical challenges faced, the following studies were not possible and are, hence, recommended for future endeavours:

(i) Economic impact assessment: studies to assess the cost-benefit analysis of using the proposed ISD and SPE dryers on fruit processing, including the mangoes and pineapples.

(ii) Food safety evaluation: studies regarding food safety, including the dust contamination and microbial load in the fruits (mangoes and pineapples), dried using the ISD and SPE dryers.

(iii) Evaluate other food types: studies to evaluate the potential of the ISD and SPE dryers on a wider range of fresh produces, including legumes, herbs, fisheries, and meat products.

The two novel dryers, thus passive-mode ISD and active mode SPE prototypes, depending on the ambient weather conditions for solar thermal energy. As such, abrupt changes in the ambient weather conditions, in particular humidity, cloud cover, wind, and erratic rainfall, affected the amount of solar energy available for the dryers, thereby compromising the drying performance.

In addition, air filters were not attached to the ISD dryer bringing issues of food safety, including a possibility of dust contamination from the incoming wind or air into the energy concentrator as well as microbial contamination of food during the drying process. Therefore, air filters should be attached to future designs and modifications of the ISD and other passive-mode solar dryers. Furthermore, the SPE prototype requires batteries and solar panels, making the fabrication process costly. Lastly, the SPE dryer consumes much energy to sustain the fruit drying operations. Thus, future efforts should target reducing the energy demand for the SPE dryer.

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# RESEARCH OUTPUTS

## (i) Publications

Ssemwanga, M., Makule, E., & Kayondo, S. I. (2020). Performance analysis of an improved solar dryer integrated with multiple metallic solar concentrators for drying fruits. Solar Energy, 204, 419-428. https://doi.org/10.1016/j.solener.2020.04.065

Mohammed, S., Edna, M., & Siraj, K. (2020). The effect of traditional and improved solar drying methods on the sensory quality and nutritional composition of fruits: A case of mangoes and pineapples. Heliyon, 6(6), e04163. https://doi.org/10.1016/j.heliyon.2020.e04163

## (ii) Poster presentation