DEVELOPMENT AND PERFORMANCE EVALUATION OF A SOLAR DRYER INTEGRATED WITH THERMAL ENERGY STORAGE MATERIALS FOR DRYING AGRICULTURAL PRODUCTS

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A Dissertation submitted in partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Sustainable Energy Science and Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

Passive solar dryers are essential in reducing post-harvest losses of vegetable and fruits particularly in developing countries in Africa. Most simple passive solar dryers are being developed in developing countries, but the challenge is the sporadic nature of solar energy, resulting in reduced performance and rendering them ineffective during periods without sunlight. In addition, Techno-economic analysis (TEA) and Life cycle assessment (LCA) have been neglected in most of the studies on solar dryers (SD). In this study, a novel solar dryer incorporating soapstone as a thermal energy storage (TES) system to prolong the drying time was designed, constructed, and evaluated for its performance in terms of TEA and LCA. Experiments were carried out to compare the performance of the developed dryer in two configurations: With and without thermal energy storage (TES) materials. The results were evaluated alongside open-sun drying (OSD) with 50 kg of fresh carrots as well as fresh pineapples on separate occasions. The drying durations were recorded as 12 hours for the dryer with TES, 23 hours for the dryer without TES, and 50 hours for OSD. Notably, the TES-integrated dryer could provide energy for approximately 3–4 hours after sunset. The dryer was found to have a thermal efficiency of 45%, a collector efficiency of 43%, and a storage efficiency of 74.5%. The dryer combined with TES materials proved to be more efficient in retaining nutrients in the dried products compared to the dryer without TES materials and OSD based on proximate study. The economic analysis showed that the annual savings for the dryer's 20 years of operation are $ 9814.5 for pineapple and $ 9121.2 for carrots. The cumulative present worth was $ 62 232.7 for pineapples and $ 57 836.3 for carrots. It was found that the pineapples payback period was 1.5 years, whereas for carrots payback was 1.6 years. The LCA revealed that steel materials had higher environmental impact items in material extraction and fabrication compared to aluminum materials for both the midpoint and endpoint categories. Based on techno-economic TEA and LCA assessments, the fabricated solar dryer is economically feasible and environmentally friendly. Solar dryers incorporating soapstone have demonstrated potential as efficient technology for minimizing post-harvest losses especially in developing countries in Africa.

DECLARATION

I, Evordius Laurent Rulazi, hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation, titled *"Development and Evaluation of a Solar Dryer Integrated with Thermal Energy Storage Materials for Drying Agricultural Products"* is my own original work and has not been submitted to any institution for the award of a degree.

23/04/2025

Evordius Laurent Rulazi — Date

The above declaration is confirmed by:

24/04/2025

Prof. Thomas Kivevele — Date

23.04.2025

Dr. Baraka Kichonge — Date

24/4/2025

Dr. Janeth Marwa — Date

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Senate of the Nelson Mandela African Institution of Science and Technology a dissertation entitled "*Development and evaluation of a solar dryer integrated with thermal energy storage materials for drying agricultural products*'' in partial fulfilment of the requirements for the Degree of Doctor of Philosophy in Sustainable Energy Science and Engineering at Nelson Mandela African Institution of Science and Technology, Arusha Tanzania.

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DEDICATION

In honor of my beloved children, Lisa Evordius Rulazi, Lalian Evordius Rulazi, and Angel Evordius Rulazi, I present this work with the earnest wish that they will excel in their studies and strive to enhance the world, thus fostering an improved quality of life for all.

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LIST OF ABBREVIATIONS AND SYSMBOLS

C_a	Annualized capital cost (USD)
C_b	Selling price of 1 kg of dried product (USD)
C_{ds}	Total cost of drying 1 kg of product (USD)
C_{ds}	Total cost of drying 1 kg of product (USD)
C_{fp}	Cost of fresh product (USD/kg)
C_m	Annualized maintenance cost (USD)
C_s	Cost of drying 1 kg of dried product (USD)
D_d	Number of days used to dry one batch of the product (days)
F_c	Capital recovery factor
F_{pi}	Present worth factor
M_f	Weight of fresh product (kg)
M_w	Moisture loss from the drying product (kg)
M_y	Weight of product dried in the dryer (kg)
P_j	Present worth of savings (USD)
S_1	Savings during first year
S_j	Year-wise savings of the dried product (USD)
S_{kg}	Savings per kilogram of the dried product (USD)
V_s	Annualized Salvage value (USD)
t_d	Drying time (hrs)
ATC	Arusha Technical College
COP	Coefficient of Performance
COSTECH	Commission for Science and Technology
d	Interest rate (%)
D	Number of drying days in a year (days)
DR	Drying Rate (kg/hrs)
DT	Drying Time (hrs)
h	Specific enthalpy (kJ/kg)
i	Inflation rate (%)
LCA	Life cycle assessment
LCI	Life cycle Inventory
LCIA	Life cycle Impact assessment
MC	Moisture Contents

n	Number of years
NM-AIST	Nelson Mandela African Institution of Science and Technology
OSD	Open sun drying
PB	Payback period
PCM	Phase change materials
PEER	Partnership for Enhanced Engagement in Research
PHLs	Post-Harvest Losses
PI	Project investigator
PP	Pay Back Period (years)
RH	Relative humidity (%)
SD	Solar Dryer
SHS	Sensible heat storage
TAHA	Tanzania Horticultural Association (TAHA)
TEA	Techno-economic Analysis
TES	Thermal energy storage
USAID	United State Agency for International Development

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Fruits and vegetables can be defined from either a botanical or culinary perspective. According to Amao (2018), fruits can be described as the edible portion of a plant that comprises the surrounding tissues and seeds, whereas vegetables are plants grown for their edible parts. Fruits and vegetables offer numerous advantages such as providing nutrition to the human body (Schreinemachers *et al.*, 2018), contributing to socio-economic development (Amini *et al.*, 2021), and supporting our immune system (Baidya & Sethy, 2020; Pal & Molnár, 2021). However, despite their numerous advantages, fruits and vegetables are highly perishable crops, resulting in significant post-harvest losses (PHLs). Global PHLs in fruits and vegetables are estimated at 44% (Kumar & Kalita, 2017), whereas in Sub-Saharan Africa, the PHLs in fruits and vegetables range from 30% to 80% depending on the type of crop (James & Zikankuba, 2017).

The widely adopted method by farmers to minimize post-harvest losses, especially in developing nations is OSD. One of the earliest, least expensive, and most basic traditional techniques is OSD, in which goods are stretched out on the ground and periodically mixed until they reach the desired dryness (Getahun *et al.*, 2021). Although open sun drying is cost-effective and straightforward, it has several limitations, including extended drying times, the risk of insect contamination, and the degradation of product quality (Akoto *et al.*, 2018; Naing & Soe, 2021; Sahdev, 2014; Tiwari, 2016; Yarkwan & Uvir, 2015), loss of color (Rehman & Rubab, 2020), and complex in controlling drying parameters such as temperature, velocity and humidity (Lingayat *et al.*, 2020). To overcome the difficulties presented by OSD, small-scale solar drying solutions are being developed (Raju *et al.*, 2013). Solar dryers are drying technologies that safeguard products from contamination. In addition, solar dryers provide sufficient temperatures and low relative humidity, resulting in good quality of the dried products (Bharadwaz, 2020).

Solar dryers can be classified as either active or passive according on how the air flows (El-Sebaii *et al.*, 2002). Active solar dyers are ideal for commercial use because they typically include active parts like a fan or heat pump to deliver heated air into the drying chamber (Balasuadhakar *et al.*, 2016). Active solar dryers use a lot of fossil fuel and demand large capital expenditures (Lakshmi *et al.*, 2021), rendering them inappropriate for rural regions, especially those in Sub-Saharan Africa, where financial resources are scarce and electrification rates are low (Matavel *et al.,* 2021). Due to their many benefits, including low maintenance costs and low capital investment, passive solar dryers are ideal for small-scale holders and agro-processors with limited resources, like those in rural Sub-Saharan Africa (Balasuadhakar *et al.,* 2016; Matavel *et al.,* 2021). Because passive solar dyers are entirely dependent on the availability of solar radiation, their most major disadvantage is their intermittent nature of solar radiations (Matavel *et al.,* 2022). Because of this, passive solar dryers are useless on overcast or nighttime days, necessitating the development of alternate methods. Agricultural products can be dried more efficiently and with less time if passive solar dryers are combined with TES materials (Alva *et al.,* 2017; Gilago & Chandramohan, 2023; Khalil *et al.,* 2023).

The TES materials provide continual drying of agricultural products by storing thermal energy during the day when there is sufficient solar energy and releasing it when sunlight is not available (Mugi *et al.,* 2022). The use of phase change materials (PCM) for agricultural drying applications has been the main focus of the majority of earlier research (Bhardwaj *et al.,* 2017; Ebrahimi *et al.,* 2021; El-Sebaii & Shalaby, 2017; Gilago & Chandramohan, 2022; Lad *et al.,* 2023; Rakshamuthu *et al.,* 2021; Reyes *et al.,* 2019; Shalaby *et al.,* 2020; Singh & Mall, 2020; Vigneshkumar *et al.,* 2021). The main problem with PCM is that it requires strict control over the process's temperature range during charging and discharging. It is difficult to satisfy this requirement in basic solar dryers due to the sporadic availability of solar radiation. Although sensible thermal energy storage (STES) materials such as granite, soapstone, sandstones, limestone, and gravel are successful in simple sun dryers, their application has received very little attention. The STES materials have many benefits, including non-toxicity, preservation of product quality, cost-effectiveness, enhanced efficiency, and reduced drying times (Ayyappan *et al.,* 2016; Bennamoun, 2013; Bhardwaj *et al.,* 2020; Cetina-Quiñones *et al.,* 2021; Srinivasan *et al.,* 2021).

Because of its thermal qualities and historical accessibility, soapstone in particular has been utilized for a variety of applications, such as making home utensils and tiles. In an experimental study comparing granite and soapstone for energy storage, Kakoko *et al.* (2023), found that soapstone outperformed granite as a TES material for solar drying technologies and solar power generating applications. According to Pirinen (2005), the density and specific heat capacity of the of soapstone is higher compared to other natural rocks, for example the density is about 2.98 g/cm^3 and the specific heat capacity ranging 0.9-1.1 kj/kg ^{o}C, which is about 20% more compared to other natural rocks. Still, not much research has been done on using soapstone as a TES material for drying agricultural products, even though it has strong thermal storage qualities. The purpose of this work is to examine soapstone's potential as an energy-storing material for agricultural product drying in a passive solar dryer. The study will also include the quality assessment of the dried products in the constructed solar dryer and comparisons with OSD.

In addition, TEA and LCA are very important aspect to analyze when developing a new technology. The TEA helps to provide understandings of financial viability of the developed solar dryer. According to Selvanayaki and Sampathkumar (2017), there are not many solar drying systems available that satisfy technical and techno-economic requirements. Moreover, newly developed technologies are important for providing socio-economic development to society; however, they can also contribute to environmental impacts. This has made it necessary for some of the developing partners and financial institutions to show a very big concern for emerging technologies and the need to conduct LCA for the sustainability of the projects (Moni *et al.,* 2020). The LCA is a procedure that is systematic, extensive, and internationally standardized and is used to quantify all pertinent emissions, resource use, environmental and health effects, and resource depletion concerns related to any goods or services (WOLF *et al.,* 2010). Therefore, the general objective of this study is to fabricate a solar dryer integrated with TES materials for the drying of agricultural products and then evaluate its performance in terms of TEA as well as LCA.

1.2 Statement of the Problem

Postharvest losses (PHLs) pose significant threats to food security, particularly in developing countries. In Tanzania, for example, PHLs for cereal crops are estimated to range between 20% and 40% (Maziku, 2019), and exceed 40% for vegetables and fruits (Dome & Prusty, 2017). These losses contribute directly to food insecurity and hunger by reducing food supplies, and they lead to malnutrition due to inadequate dietary intake. Furthermore, they can trigger economic decline as diminished food availability weakens local economies and livelihoods. One of the primary contributing factors is the limited access to essential processing and drying technologies.

Passive solar dryers provide simple drying solution that can significantly reduce PHLs, especially in rural areas with limited electrification and funding. However, their operation is hindered by their dependence on sunlight, which results in poor performance. This research seeks to overcome these limitations by developing and evaluating a solar dryer integrated with thermal energy storage (TES) materials, specifically comparing the effectiveness of soapstone as an energy storage medium against traditional open sun drying.

Historically, soapstone, due to its good thermal properties, has been widely used across civilizations for making valuable things such as cooking vessels, sculptures, countertops, smoking pipes, and heating stoves. While most of the works have been focusing to improve the performance of the active solar dryers, the application of the soapstones to improve the performance of the passive solar dryers has yet to be explored. This study uniquely examines its application in passive dryers, thereby filling a research gap for resource-constrained rural areas.

Moreover, while most research on solar dryers has focused primarily on enhancing their performance, essential aspects like TEA and LCA, which are crucial for the sustainability of solar dryers, have often been overlooked. Therefore this study aims to address these gaps by offering a comprehensive evaluation of the performance, economic feasibility, and environmental impact of a soapstone-integrated solar dryer, thereby contributing to sustainable food security solutions in developing countries.

1.3 Rationale of the Study

Smallholder farmers and agro-processors, especially in rural areas, require simple and cheap drying technologies to dry their agricultural products in order to reduce PHLs. This is because complex drying technologies such as heat pumps, electric dryers, freeze-drying, and microwaves require high investment and are highly energy-demanding; hence, their application is limited in rural areas where the electrification rate is low and financial resources are limited. Passive solar dryers are simple and cheap technologies that can be the best options for smallholder farmers and agro-processors in rural areas for drying their agricultural products. However, the intermittent nature of passive solar dryers makes their performance poor and unreliable. Therefore, the integration of TES materials with passive dryers can prolong the drying time and improve the dryer's performance. This drying technology will help smallholder farmers and agro-processors in rural areas to dry their agricultural products and reduce PHLs in Tanzania.

1.4 Research Objectives

1.4.1 General Objective

The general objective of this study was to develop and evaluate the performance a solar dryer integrated with thermal energy storage materials for the drying of agricultural products.

1.4.2 Specific Objectives

(i) To evaluate thermal and drying performances of a solar dryer incorporated with thermal energy storage materials for drying vegetables and fruits.

(ii) To carry-out techno-economic analysis of a solar dryer incorporated with TES materials for drying of vegetables and fruits.

(iii) To conduct life cycle assessment of a solar dryer incorporated with TES materials for drying of vegetables and fruits.

1.5 Research Questions

(i) What is the technical performance of a novel solar dyer incorporated with TES materials?

(ii) Is a newly developed solar dryer incorporated with TES materials affordable and cost-effective for smallholder farmers?

(iii) What are the possible environmental impacts of the solar dryer incorporated with TES materials?

1.6 Significance of the Study

This study is crucial because it contributes to the improvement of passive solar dryers, which are commonly used by smallholder farmers in developing countries, especially in rural areas, but their intermittence nature makes them unreliable. The integration of passive solar dryers with soapstone rocks as thermal energy storage materials has been reported to improve the drying efficiency and quality of the dried products. Numerous passive solar dryers have been constructed in developing nations; however, most of the work has concentrated on the performance analysis of the dryers. This neglects the TEA, which is very important for providing insight on the financial visibility of the developed dryer. In addition, LCA is crucial for understanding the effects of developed technology on the environment. However, LCA has neglected most of the newly developed technologies. Therefore, these studies will contribute to the understanding of the technical performance of the developed solar dryer as well as TEA and LCA.

1.7 Delineation of the Study

This study assesses the performance of a SD incorporated with TES materials for drying food products. It presents in details technical performance, TEA aspects, and LCA of the dryer. The first chapter outlines the background of the study, problem statement, rationale, objectives, research questions, and significance. The second chapter reviews existing literature on post-harvest losses, solar drying techniques, thermal energy storage, and the quality of dried products, TEA, and LCA. The third chapter details the materials and methods used for fabrication, performance evaluation, TEA and LCA. The fourth chapter provide in-depth discussions on the results related to performance, product quality, techno-economics, and environmental impacts. The final chapter offers key conclusions and recommendations drawn from this research study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Solar dryers incorporated with TES materials are emerging as a promising solution for drying agricultural products. The literature review aims to synthesize existing research, highlight current trends, and identify gaps in the field of solar drying technologies. The review is structured into several key sub-sections; post-harvest losses, traditional drying methods, solar drying technologies, thermal energy storage materials, quality of dried agricultural products, TEA, and LCA. The primary objective is to provide a comprehensive overview of previous research on developed dryer, discuss the current state and advancements in the field, and identify existing gaps to propose areas for future research. This structured approach enables a detailed assessment of the potential and limitations of the developed SD, particularly those incorporated with TES materials.

2.2 Post-Harvest Losses

Post-harvest losses (PHLs) refer to the measurable quantifiable and non-quantitative losses of agricultural products that occur from harvest to consumption (Bendinelli *et al.,* 2020). The PHLs are a significant issue, especially in developing countries, affecting food security and the economy (Zorya *et al.,* 2011). Post-harvest losses are estimated to range from 20–40% for cereal crops and 40–50% for fruits and vegetables in developing countries (Muthuvairavan *et al.,* 2023). According to Zorya *et al.* (2011), PHLs can take different forms, such as a reduction in the quantity of food produced (physical losses) or a deterioration in the quality of the produce (quality losses), which may lead to financial losses (economic losses).

Post-harvest losses can be attributed to a number of issues that occur across the food supply chain. These include harvesting practices, lack of proper transportation infrastructure and improper transportation facilities, processing, storage, improper parking materials, insects and pests, lack of reliable marketing, environmental factors, technological advancements, and management factors (FAO, 2019). According to Mohamed *et al.* (2024), harvesting practices such as improper timing of the of the harvesting period can affect impact the products' quality and shelf life. For example, early harvesting before the product reaches full maturity can results into poor flavor and nutritional loss, while late harvesting can cause the product to become overripe and more prone to deterioration. In addition, using the wrong harvesting tools might mechanically harm the products and leave them vulnerable to microbial adherence and spoilage.

Lack of proper transportation infrastructure and proper transportation facilities can lead to loss of quality of the products and decay (Etefa *et al.,* 2022). Fresh products are required to be transported to the market or stored immediately after harvesting. Most of the agricultural products especially developing countries are grown in rural areas where road infrastructure is very poor, and it takes some days to transport fresh products from farms to markets which leads to significant losses (Elik *et al.,* 2019). Improper packing materials can led to PHLS, the majority of farmers choose low-quality, improper, and unfit materials and containers for their products, which can result in mechanical problems including bruising, abrasion, decay, chilling, rotting, and softening (Kasso & Bekele, 2018). Agricultural products are normally attached to insects and pests during all stages, from seedling to storage. Insects and pests are major threats to agricultural products and responsible for direct and indirect losses (Tadesse, 2020).

Processed agricultural products are more stable, more easily digested, and allow for a more varied diet, providing customers with more options and a greater variety of vitamins and minerals. Insufficient processing, such as inadequate drying or cleaning, can lead to increased moisture content or contamination, contributing to spoilage and loss of quality (FAO, 2019). Technological and management factors are among of the factors contributing to PHLs (Agriculture, 2019). For example lack of proper technology for drying and storage can lead to PHLs, on other hand lack of good management practice such as proper training for post-harvest loss management can also led to PHLs.

2.2.1 Main factors contributing to Post-Harvest Losses in Fruits and Vegetables

Fruits and vegetables are very important products for providing essential nutrients in bodies however, they more susceptible to PHLs compared to other agricultural products. According to Rahman (2020), fruits and vegetables generally have high water content (70-95%), making them more perishable than other agricultural products. High moisture levels create an ideal environment for microbial growth, leading to rapid spoilage. In addition, fruits and vegetables are often more delicate and prone to bruising, cuts, and other physical injuries during the entire supply chain. These injuries can cause the development of pathogens and spoilage, leading to a significant amount of loss (Muthuvairavan *et al.,* 2023). Table1 shows PHLs of various food substances, as seen from the table, the PHLs in vegetables and fruits range from 40–50% higher than other agricultural products due to their perishability.

Table 1: Post-harvest losses of some products

Products	PHLs (%)
Cereals	20-40
Pulse and oil crops	10-20
Roots and tubers	10-20
Vegetable and fruits	40-50
Meat	20-30
Fish	20-30
Diary	10-20

Muthuvairavan *et al.* (2023)

2.2.2 Impact of Post-Harvest Losses on Food Security and Economy

Post-harvest losses have a profound impact on food security and the economy. High levels of PHLs reduce the availability of food, exacerbating hunger and malnutrition, particularly in regions that are already food insecure (FAO, 2019). According to Capone *et al.* (2016), every year, one third of all the food produced for human consumption about 1.3 billion tons, which is equivalent to $1 trillion is lost every year at global level along food supply chains thus affecting the sustainability of the food system. The PHLs can cause nutritional deficiencies due to losses in nutritional value, this can cause reduced dietary diversity and lack of essential nutrients, leading to malnutrition. In addition, PHLs can lead to reduced food availability and instability of food supply when significant quantities of food are lost, leading to hunger, insufficient food availability and high prices (Kiaya, 2014). Post-harvest loss can also have significant economic impact. For example, in East Africa and the near east, the economic losses in the dairy sector due PHLs is estimated about $ 90 million/year (Kiaya, 2014). According to Nayak *et al.* (2018), PHLs can affect farmers income, hindering them from investing in better farming practices and other economic developments. The PHLs may also have an impact on business enterprises that process, store, and distribute goods since their capability to remain viable and create jobs may be hampered by the decreased amount and quality of produces (Agriculture, 2019).

2.2.3 Post-Harvest Losses in Tanzania

In Tanzania, PHLs are particularly pronounced due to several factors. The tropical climate in Tanzania accelerates the spoilage of perishable goods like fruits and vegetables (Mgonja & Utou, 2017). Limited access to modern storage, processing and transportation facilities exacerbates the problem of PHLs (Agriculture, 2019). The reliance on traditional drying methods, such as open sun drying, contributes to high levels of PHLs due to inefficiency and exposure to contaminants (Ngowi & Selejio, 2019). In addition, the annual average cereal crop production in Tanzania is estimated at 9 455 000 tons; however, about 40% of the food produced is lost through PHLs, which is equivalent to 3 782 000 tons (Agriculture, 2019). Addressing these challenges requires the adoption of improved drying technologies, such as solar dryers integrated with TES materials which can significantly reduce PHLs and enhance the quality and shelf-life of dried products.

2.3 Traditional Drying and Preservation Methods

Traditional food drying methods have been used for centuries to preserve agricultural products, with OSD being the most common. Traditional food preservation methods can fall into three categories: Canning, freezing, and drying (Gunathilake *et al.*, 2018). Canning is the process of heating food, sealing it in sterilized jars or cans, and then boiling the containers to sterilize or destroy any leftover microorganisms (Dwivedi *et al.,* 2017). During canning process, the majority of bacteria are eliminated, which lessens their influence on the safety and quality of food. However, canned foods have been linked to the presence of a number of unwanted chemical pollutants (Zheng *et al.*, 2023). Freezing is one of the ancient food preservation method in which heat is extracted from the outer surface of the product by a cooling medium (Năstase *et al.,* 2016). Freezing can also be a challenge in rural areas, notably in underdeveloped nations with low rates of electrification and little financial resources. Drying is considered one of the best food preservation techniques as it reduces water from the products to a level where bacteria cannot grow, decreases volume and weight, prolongs shelf life, preserves agricultural products, and makes it easier to transport, store, and package them (Calín-Sánchez *et al.*, 2020). Drying is one of the oldest methods used by mankind to reduce PHLs, it involves the application of heat to remove moisture from the products to a level safe for storage (Belessiotis & Delyannis, 2011). According to Gunathilake *et al.* (2018), drying can be grouped into two main categories, namely, open-sun drying (natural drying) and solar drying (artificial drying).

Other traditional food preservation methods that are commonly used are smoking and salting. Smoking involves hanging over the products near the campfire to quicken the drying process (Andrés *et al.*, 2007). Smoking technology has experienced an important evolution. Products to be smoked were once directly exposed to smoke in the same chamber; but, in contemporary systems, the smoking sources and products are housed in separate chambers. Smoking is commonly used in tobacco processing. Salting is another one of the oldest traditional food preservation method which can be traced back 3500 to 4000 years B. C (Shenderyuk & Bykowski, 2020). Despite the fact that this preservation method is relatively cheaper and commonly used, the detrimental effects of consuming too much salt in the diet, which has been connected to hypertension and therefore an elevated risk of cardiovascular disease, have come to light more frequently, especially in the context of fish drying (Albarracín *et al.*, 2011). These traditional methods, while cost-effective, have significant limitations that affect the quality and safety of the dried products.

2.3.1 Open Sun Drying

Due to its affordability and convenience of usage, OSD is the most and widely applied traditional techniques (Sontakke & Salve, 2015; Vaghela *et al.*, 2018). Evidence suggests that Egyptian tribes people on the lower Nile used the harsh desert sun to dry fish and poultry as early as 12 000 B. C (Shephard, 2006). Dry climate areas were preferred for food drying. According to Shephard (2006), in almost all areas of ancient world, OSD was practiced from the very earliest days for example, when European arrived in the new world in the sixteen century, they found long established traditional drying methods.

The open sun drying involves spreading products on the ground and regularly turned often until adequately dried. Figure 1 shows mechanism of OSD method. According to Gorjian *et al.* (2021), crops to be dried are spread on the clean surface, short wavelength solar radiation falls on the products. The surface of the drying products absorbs some of the solar light, while the remainder is reflected back. As a result of the absorbed solar radiation being converted into thermal energy, the temperature of the products rises. Long wave radiations are thus lost from the drying products' surface to the surrounding air through the damp air. Convective heat loss occurs when wind blows across the product at the same time. The end effect is that the substance becomes dried as the moisture evaporates and is lost to the surrounding air.

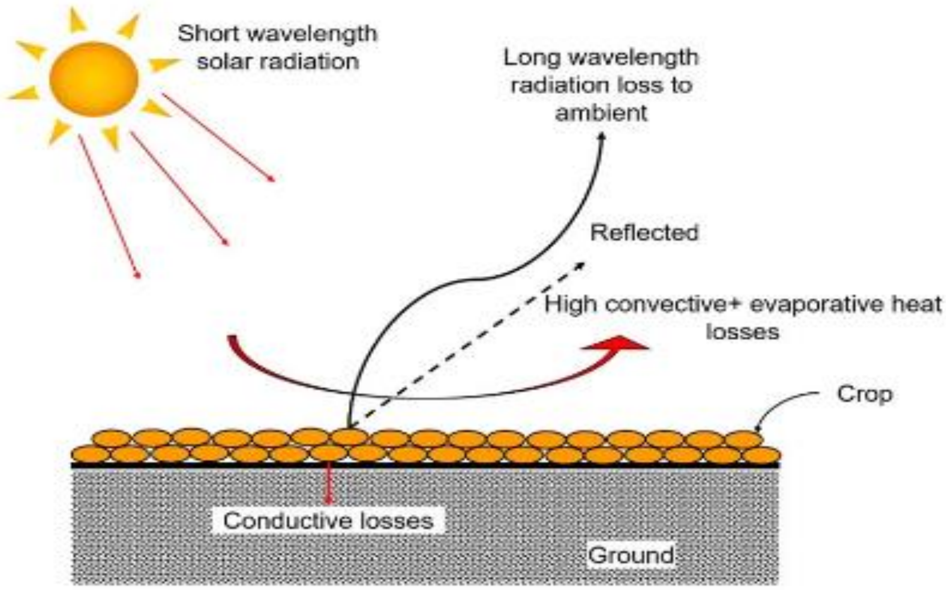

Figure 1: Open sun drying (Gorjian *et al.*, 2021)

2.3.2 Advantages and Limitation of Open Sun Drying

Open-sun drying has some advantages, low initial investments cost, simplicity of use and accessibility, ability to accommodate a large amount of products at a time, environmentally friendly (Sontakke & Salve, 2015). In addition, because of its cultural significance, OSD is generally accepted in society. Despite all of its benefits, OSD has drawbacks, including a lengthy drying period, insect contamination, and a decline in the quality of dried goods (Akoto *et al.*, 2018; Naing & Soe, 2021; Sahdev, 2014; Tiwari, 2016; Yarkwan & Uvir, 2015), loss of color (Rehman & Rubab, 2020), and complex in controlling drying parameters such as temperature, velocity and humidity (Lingayat *et al.*, 2020). In order to overcome the difficulties presented by OSD, solar drying solutions are being developed. Table 2 summarizes the advantages and limitations of open sun drying.

Table 2: Advantages and limitations of OSD

Advantages	Limitations
Low Cost	Highly dependent on weather conditions
Minimal investment in equipment	Exposure to contamination (dust, insects, animals)
Simplicity	Uneven drying due to lack of precise control
Easy to perform with traditional knowledge and techniques	Risk of spoilage if weather conditions are not optimal
Sustainability	Long drying times can lead to nutrient loss
Uses natural sunlight, environmentally friendly	Requires large drying area
Accessibility	Quality can vary widely
Suitable for small-scale farmers and rural communities	Limited scalability for commercial production
Does not require electricity or fuel	Limited to regions with suitable climates
Can dry large amount of products simultaneously	Labor-intensive due to the need for regular turning

2.3.3 Efforts to Enhance Traditional Drying Methods

Various efforts have been made to improve traditional drying methods to address their limitations. These include the development of improved drying structures such as solar dryers, which offer a more controlled drying environment. Solar dryers can expressively reduce drying time and improve product quality by protecting them from contaminants and providing consistent drying conditions (Chojnacka *et al.*, 2021). Modern passive dryers represent an evolution of traditional techniques, combining simplicity with improved efficiency and product quality (Matavel *et al.*, 2021).

2.4 Solar Drying Technologies

Solar dryers have emerged as an advanced alternative to traditional drying methods, offering numerous benefits including improved drying efficiency, product quality, and reduced post-harvest losses.

2.4.1 Introduction to Solar Dryers

Solar dryers dry agricultural products by using sun energy. These devices absorb solar radiation, convert it into thermal energy, and transfer that energy to the products, facilitating the drying process (El-Mesery *et al.*, 2022). Solar dryers provide elevated temperatures, lower relative humidity, and enhanced airflow around the products. These conditions lead to faster drying, reduced moisture content, and less spoilage throughout the drying process (Bharadwaz, 2020). Figure 2 shows a schematic diagram of a basic solar dryer. The solar collector raises the temperature and lowers the humidity as the fresh air travels through it. The hot air from the solar collector then enters the drying chamber to dry the products.

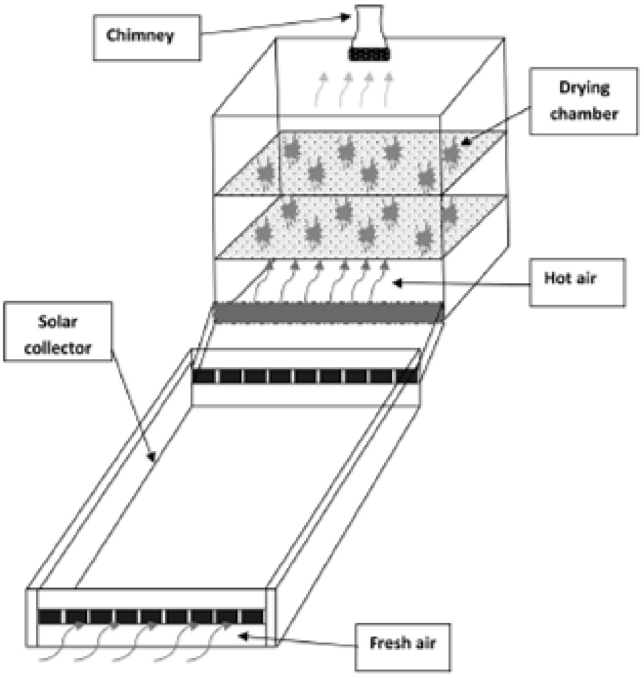

Figure 2: Schematic diagram of a basic solar dryer

2.4.2 Types of Solar Dryers

A wide different of solar drying technologies are currently present on the market for drying agricultural products. According to Jha and Tripathy (2021), solar dryers can be divided into three main categories depending on the mechanism of air flow; natural (passive), forced (active), and hybrid solar dryers. Passive and active solar dryers can further be grouped into three categories; direct solar dryer, indirect solar dryer and mixed model solar dryer. Hybrid solar dryers can be renewable-type or non-renewable-type. A hybrid solar dryer combines solar energy with an auxiliary heating source (such as electricity, TES materials) to ensure consistent drying regardless of weather conditions. Figure 3 shows the classification of solar drying systems.

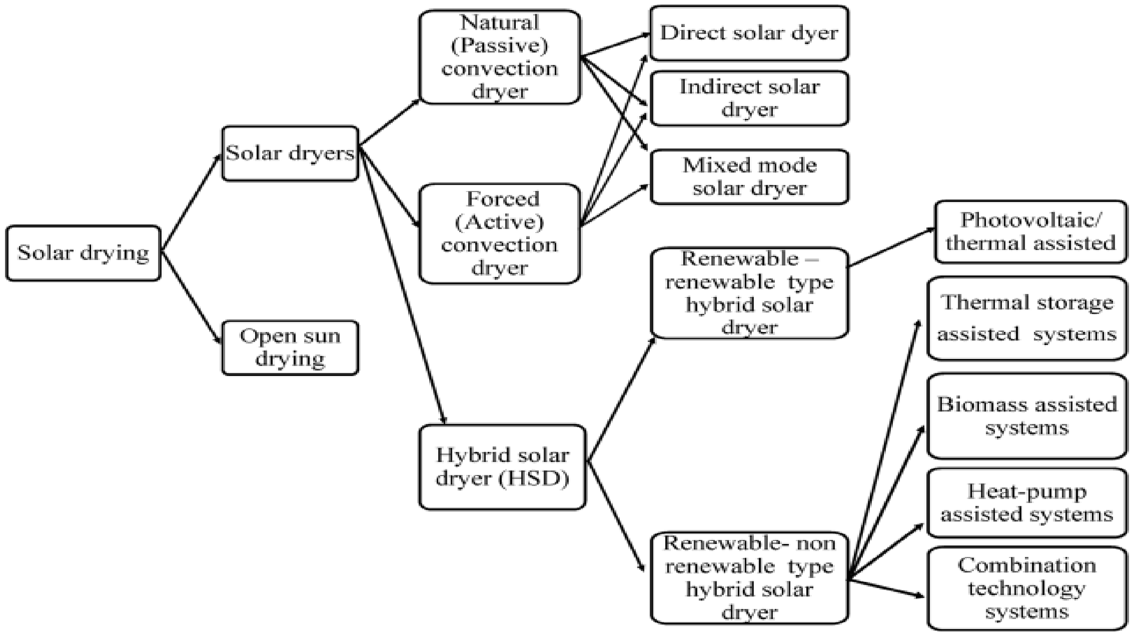

Figure 3: Classification of the solar dryers (Jha &Tripathy, 2021)

According to Balasuadhakar *et al.* (2016), typically, active solar dyers are integrated with active parts like heat pumps or fans to transfer warm air from the collector to the drying chamber, whereas as passive solar dyers are types of solar dyers that do not incorporate active components, hence the drying process depends on natural movements. Passive solar dryers are environmentally friendly compared to active solar dryers. The main limitation of passive solar dyers is the intermittent nature of solar energy, which leads to poor performance (Matavel *et al.*, 2021). Figure 4 shows the schematic diagram of an indirect passive solar dryer. As it can be seen from Fig. 4, the solar dyer is not incorporated with any active components, and air is heated and move into the solar collector without use of any active component. Figure 5 shows an indirect active solar dryer. The dryer has been integrated with active components such as PV panels and a fan.

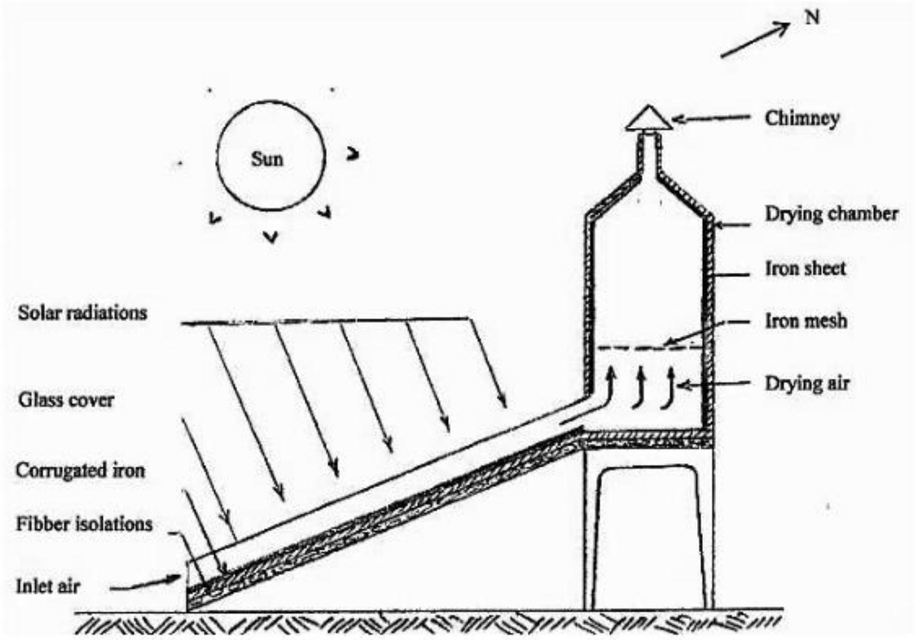

Figure 4: Schematic diagram of a passive solar dryer (Murad, 2018)

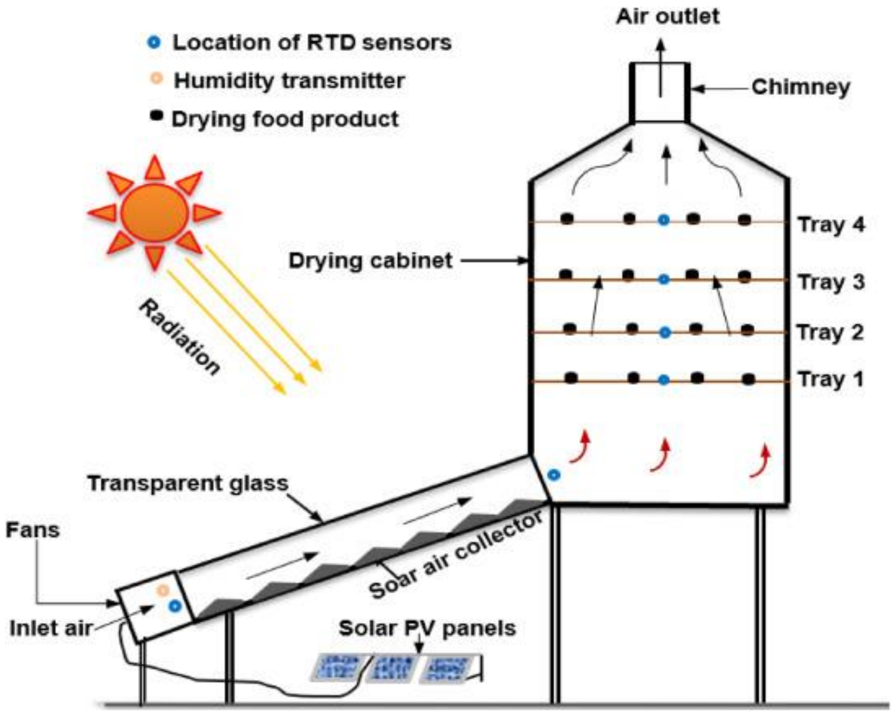

Figure 5: Diagram of active solar dryer (Gilago & Chandramohan, 2022)

2.4.3 Applications of Solar Dryers

Solar dryers are perfect for drying a diverse array of agricultural items, including fruits, vegetables, and grains. They can be used at different scales, from small household units to larger commercial operations. Solar dryers are particularly beneficial in regions with high solar insolation and where traditional drying methods are inadequate (Udomkun *et al.*, 2020). Figure

6, depicts heat pump solar dryer which is mostly used for an industrial application in large scale-commercial drying.

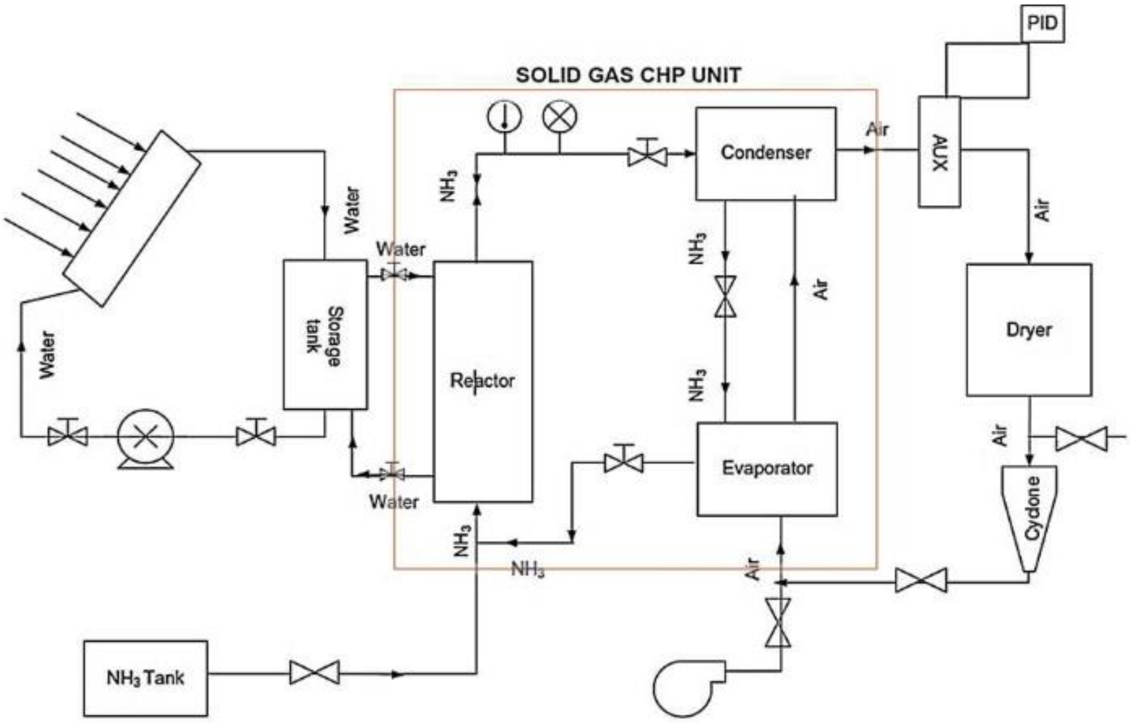

Figure 6: Schematic diagram of heat pump solar dryer (Goh *et al.*, 2011)

2.4.4 Suitability for Different Scales of Operation

The scalability of solar dryers makes them suitable for various levels of operation. Small-scale solar dryers are ideal for individual households and small farms, providing a cost-effective solution for drying produce. Active solar dyers are suitable for large-scale drying operations, they also require huge investment and consume significant amount of fossil fuel (Lakshmi *et al.*, 2021). Passive solar dryers are suitable especially in rural areas where electrification rate and financial resources are limited hence, suitable for small scale operation and commonly used in rural areas especially developing countries (Balasuadhakar *et al.*, 2016). The integration of thermal energy storage materials into solar dryers (hybrid) can further enhance their efficiency and reliability, particularly in regions with intermittent solar availability. This approach can help to overcome some of the limitations of solar dryers, making them a more viable option for reducing PHLs and improving food availability. Table 3 provides a summary of the suitability of different types of solar dryers for various scales of operation.

Table 3: The suitability of solar dryers for various scales of operation

Type of Solar Dryer	Description	Suitable Scale of Operation	Advantages	Limitations
Passive Solar Dryer	Utilizes natural convection for air movement, with products exposed directly or indirectly to sunlight.	Small-scale, household or farm-level	Low cost, simple design, no energy consumption	Limited capacity, slower drying, weather dependent
Active Solar Dryer	Uses fans or blowers powered by electricity or solar panels to enhance air circulation and drying.	Medium to large-scale, commercial	Faster and more consistent drying, better control of conditions	Higher initial cost, requires energy source, more maintenance
Hybrid Solar Dryer	Combines solar energy with auxiliary heating (electricity, biomass) for consistent drying regardless of weather.	Medium to large-scale, industrial	Reliable drying in any weather, high efficiency	Expensive, complex system, requires reliable auxiliary energy

2.5 Thermal Energy Storage Materials

The TES materials play a crucial role in enhancing the performance of solar dryers. Thermal energy storage systems consist of materials capable of storing heat or cold, which can be utilized later under different conditions to maintain efficient drying (Cabeza *et al.*, 2015). Storage of thermal energy is a very important aspect in addressing the challenge of intermittence in solar energy sources, especially in agricultural drying applications. Energy storage enhances the efficiency of energy systems by balancing the disparity between energy supply and demand. This optimization not only improves overall performance but also contributes to capital savings (Kaviti & Deep, 2017).

2.5.1 Types of Thermal Energy Storage Materials

The TES materials can generally be classified into two types: sensible heat storage (SHS) and latent heat storage (LHS) materials. The SHS materials store thermal energy through a change in temperature, while LHS materials store energy by undergoing a PCM, for example from solid to liquid. Common SHS materials include water, rocks, and sand, while PCM such as paraffin wax and fatty acids are typical LHS materials (Faraj *et al.*, 2024). Figure 7 shows a classification of thermal energy systems. According to Faraj *et al*. (2024), SHS materials can further be grouped into liquids and solids. Latent heat storage can further be divided into three categories; liquid-gaseous, solid-liquid, and solid-solid. The solid-liquid storage forms PCM of various forms.

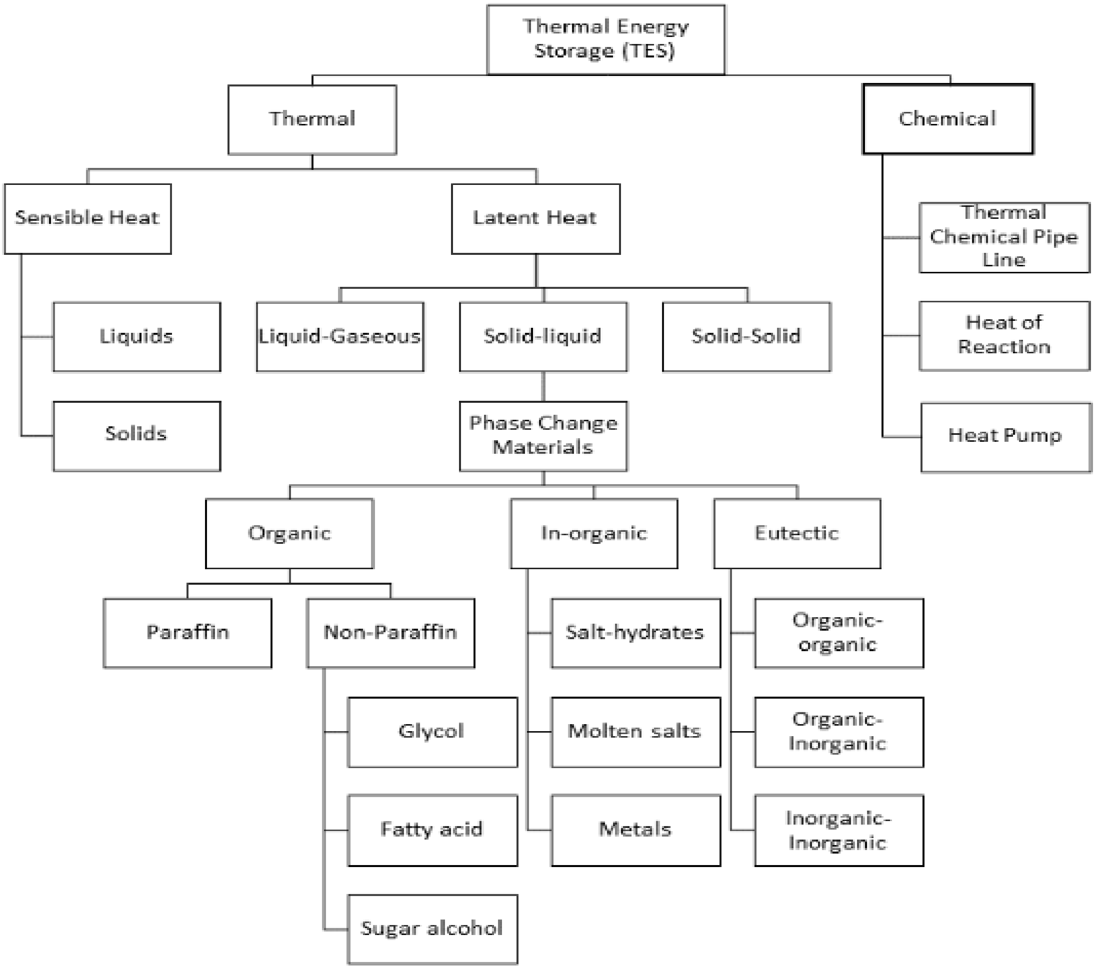

Figure 7: Classification of the thermal energy system (Faraj *et al.*, 2024)

The PCM are usually LHS materials that store and release heat through chemical bonds. The breakdown of chemical bonds with the material during the PCM's transition from a solid to a liquid or from a liquid to a solid results in thermal energy transfer (Bal *et al.*, 2010). The majority of earlier research has mostly concentrated on the use of PCM in agricultural drying applications (Bhardwaj *et al.*, 2017); however, the main problem with PCM is that it requires a strictly controlled temperature range while charging and discharging, which is difficult for simple solar dryers. In addition, phase change materials have been reported with some challenges, such as high initial cost, risk of leakage, and should be compatible with the container used (Yao *et al.*, 2022). Figure 8 shows the indirect solar dryer integrated with PCM materials for the drying of agricultural products. The PCM materials have been integrated beneath the solar collector.

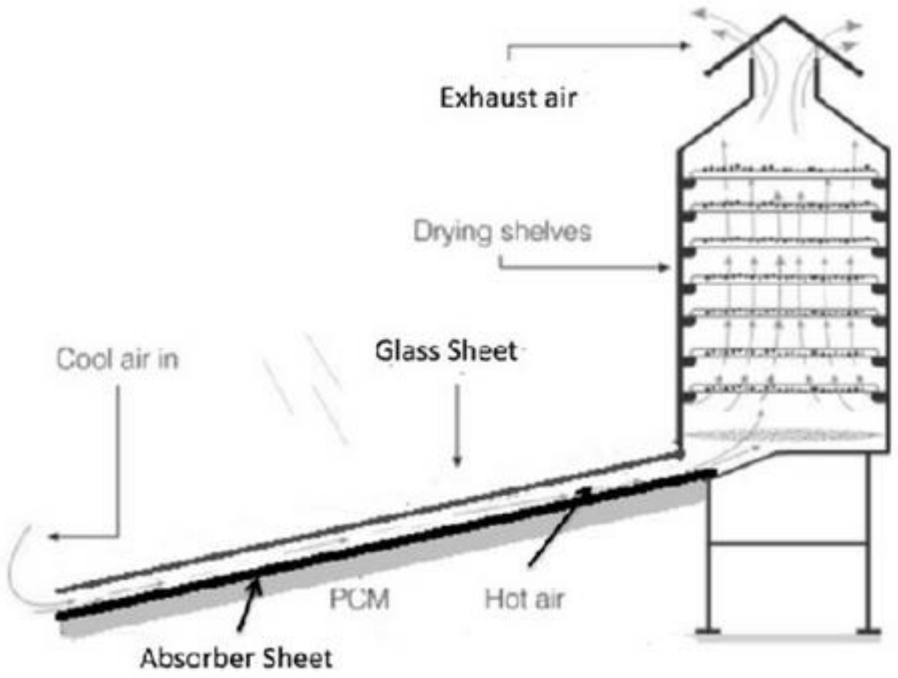

Figure 8: Schematic diagram of passive solar dryer with PCM (Tiwari, 2016)

2.5.2 Applications of Thermal Energy Storage Materials in Agricultural Drying

When compared to alternative storage technologies, thermal storage systems offer benefits including reduced startup costs and better performance (Shubham & Nain, 2021). According to Kaviti and Deep (2017), the incorporation of solar thermal energy storage can lessen the need for extra backup power, preserving fossil fuel energy supplies. Thermal energy storage techniques provide adaptable solutions that increase the sustainability of solar energy systems and lower CO_2 emissions (Koçak *et al.,* 2020). They also help reduce intermittent effects in solar dryers and improve the performance of the dryer.

Sensible TES materials are storage materials with a long history of various applications in many field such as in buildings and solar dryers to store and release heat (Li, 2016). According to Nayanita *et al.* (2022), sensible heat materials are mostly preferred for domestic-scale applications because they usually have larger thermal conductivities as compared to PCMs for solar energy applications. The most commonly used sensible heat storage materials for solar drying applications are rock, sand, sandstone, gravel, rocks, pebbles, limestone, clay, soil, bricks, quarts, reinforced concrete, and water (Mugi *et al.,* 2022). Sensible heat storage can be a best option for simple solar dryers designed especially for rural areas. Figure 9 shows the schematic diagram of active solar dryer integrated with gravel rocks as sensible thermal energy storage materials.

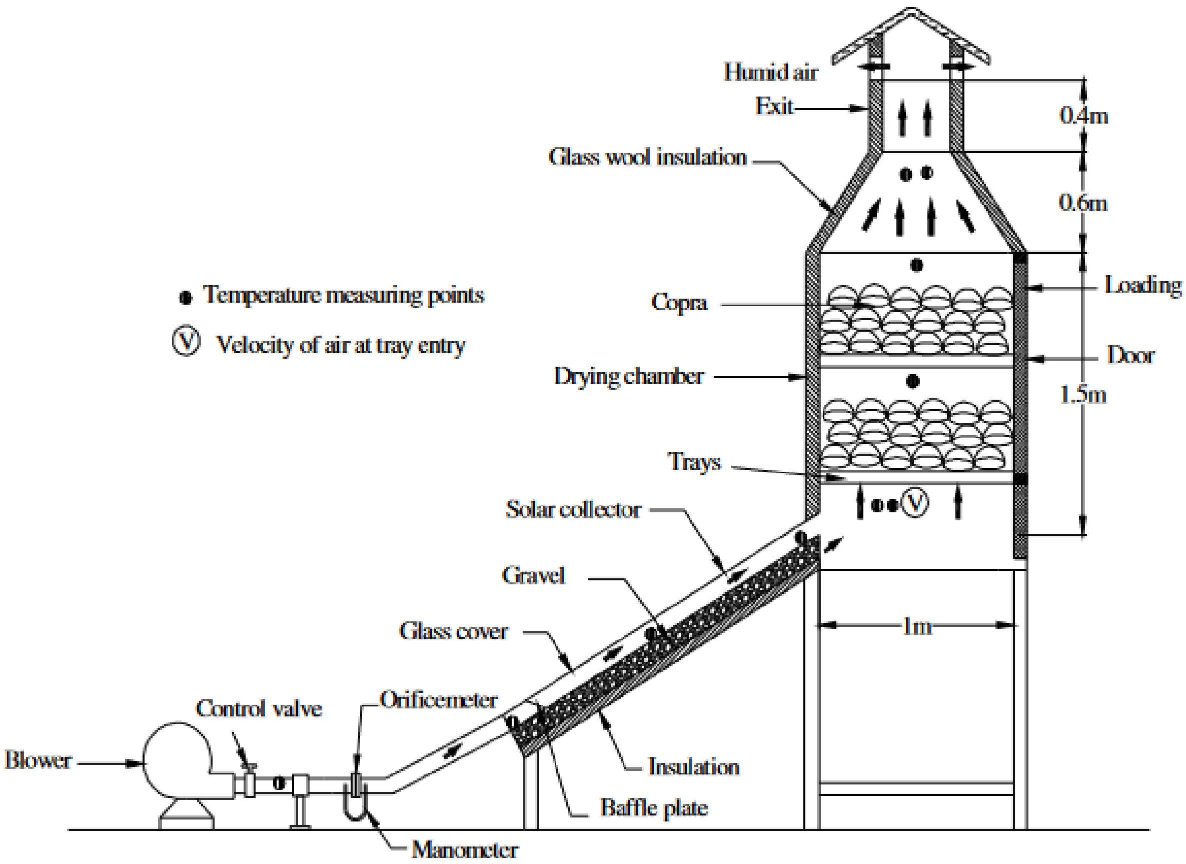

Figure 9: Schematic diagram of active solar dryer (Tiwari, 2016)

2.5.3 Soapstone Rocks as Thermal Energy Storage materials

Soapstone rocks are a promising TES material due to their high specific heat capacity and thermal conductivity. They can store large amounts of thermal energy and release it slowly, providing a steady heat source for drying. Studies have demonstrated that solar dryers using soapstone rocks as TES material achieves better drying performance compared to other rocks (Kakoko *et al.,* 2023).

Soapstone is one of the thermal energy storage materials and has been known for a long time for its good thermal properties, such as low dielectric, high density, high specific capacity, high temperature resistance (Kora, 2020). Because of their good thermal properties, soapstones have been used for different purposes in making different appliances, such as kitchen utensils, storage containers, and ornaments. Kakoko *et al.* (2023), investigated granite and soapstone experimentally for energy storage and discovered that soapstone rocks outperformed granite as TES materials for solar drying technologies and solar power generation. However, the use of soapstone as a TES material for drying agricultural products is still largely unexplored, despite its excellent heat storing qualities. Table 4 compares the thermo-physical properties of soapstone rocks with other common TES materials at 20°C. The thermo-physical of soapstone is higher than other rocks materials.

Table 4: Thermo-physical properties of thermal energy storage

Type of Materials	Density (g/cm^3)	Specific heat (J/g·K)	Thermal capacity $MJ/(m^3·K)$	Thermal conductivity (W/m· K)
molten salts	0.9−2.6	1.5	1.35−3.9	0.15−2
cofalit	3.12	0.8−1.03	2.5−3.22	1.4−2.1
castable ceramics	3.5	0.866	3.03	1.35
HT concrete	2.75	0.916	2.52	1
ROCKS				
granite	2.6−2.7	0.6−0.95	1.56−2.52	2.6−3.1
limestone	2.3−2.8	0.68−0.91	1.58−2.51	2.0−3.0
marble	2.6−2.7	0.8−0.88	2.08−2.37	2.3−3.2
quartzite	2.5−2.6	0.62−0.83	1.56−2.19	2.9−5.7
sandstone	2.2−2.6	0.69−0.95	1.49−2.51	1.7−2.9
granodiorite	2.7	0.65−1.020	1.74−2.78	2.1−2.6
gabbro	2.9−3.0	0.6−1	1.72−3.03	1.5−2.6
basalt	2.3−3.0	0.7−1.23	1.60−3.71	1.2−2.3
hornfels	2.7	0.82	2.25	1.5−3.0
schist	2.6−2.8	0.790−1.1	2.09−3.08	2.1−3.0
quartzitic sandstone	2.6−2.6	0.652	1.71−1.72	5.0−5.2
rhyolite	2.3−2.6	0.785	1.81−2.04	1.6−2.3
andesite	2.6−2.7	0.815	2.13−2.17	2.3−2.8
calcareous sandstone	2.7	0.652	1.73	4.4
steatite/soapstone	2.7−3.0	0.98−1.07	2.63−3.18	2.5
dolerite	2.7−2.9	0.87−0.9	2.31−2.61	2.2−3.0
gneiss	2.7	0.77−0.98	2.08−2.64	2.7−3.1
diorite	2.8−3.0	1	2.8−3	2.5
dolomite	2.8	0.80	2.21−2.27	2.1

Kakoko *et al.* (2023)

2.6 Quality of Dried Agricultural Products

The quality of dried agricultural products is a critical factor that influences their marketability and consumer acceptance. Proper drying techniques ensure that essential nutrients like vitamins, minerals, and antioxidants are preserved, however, poor drying methods can lead to significant nutrient loss. Crop drying is one of the fundamental process for food preservation, however, it has been reported in some studies to slightly reduces the quality of the dried products, such as color and flavor (Gunathilake *et al.*, 2018; Mongi & Ngoma, 2022). Proximate assessment is crucial to understand the quality of the dried products. According to

Hart and Fisher (2012), proximate analysis is the process of determining a collection of closely related components, including total protein and fat together.

2.6.1 Factors Affecting Quality of the Dried Products

According to Jha and Tripathy (2017), factors influencing the quality of the dried products can be grouped into three categories; dryer design, food properties and environmental factors. The design factors consider parameters related to the design of the solar dryer, such as type of solar dyer, size of the drying chamber, materials used for fabrication, air movement, loading capacity and etc. Food properties are related to the factors such as thermo-physical properties, proximate compositions, initial moisture contents, and food geometry. The environmental factors that affect the quality of the drying products are solar radiation, ambient temperature, relative humidity and wind. A suitable temperature is very important during drying in order to maintain the nutritional value of the products. Very low and high temperatures can affect the quality of the products. The temperature range of 40–70°C is recommended for drying most of the agricultural products (Belessiotis & Delyannis, 2011). Relative humidity is another environmental factor that can affect the quality of the solar dryer. Lower relative humidity accelerates the drying process, whereas higher relative humidity slows the drying process and can affect the quality of the products (Chramsa-Ard *et al.,* 2013).

2.6.2 Comparison of Drying Methods

The quality of dried food including the performance of the dryer varies significantly between different drying methods. Open sun drying often results in lower quality due to exposure to contaminants and uncontrolled drying conditions. In contrast, solar dryers, especially those integrated with TES materials, provides better control over drying conditions, leading to higher quality products. For instance, solar dryers with TES maintain more consistent temperatures, reducing the risk of over-drying or under-drying (Bhardwaj *et al.,* 2020).

Studies have shown that solar dryers integrated with TES materials are more effective in preserving the quality of dried food compared to other drying methods (Bhardwaj *et al.,* 2020). For example, Mongi and Ngoma (2022), examined the effects of SD on proximate composition for sugar profile and organic acid of mango varieties in Tanzania. It was reported that the proximate compositions slightly decrease in the protein, fat, crude fiber, ash and CHO in the dried products using solar dryer compared to the fresh products. Catorze *et al.* (2022), studied the solar energy drying system focusing on the energy savings and effect in dried food quality. The findings demonstrated that while protein and total sugar were higher in dried products than in fresh ones, the drying process decreased moisture, fat, ashes, antioxidant activity, and total phenols. In another, experiment conducted by Baloch *et al.* (2015) on proximate and mineral compositions of dried cauliflower. It was reported that drying process using the solar dryer reduced moisture contents, however increased protein, fiber, ashes, carbohydrate and minerals. Table 5 compare the quality attributes of products dried using open sun drying, solar dryers without TES, and solar dryer with TES. As it can be seen, the solar dryer with TES materials has higher efficiency and a shorter drying time compared to the dryer the dryer without TES materials and OSD.

Table 5: Performance comparison of OSD, with TES and without TES materials

Type of solar dryer	**Types of TES material used**	**Solar dryer with TES materials**	**Solar dryer without TES materials**	**Open sun drying**	**Reference**
Hybrid solar dryer integrated TES used for drying papaya and Roselle.	Gravel	Drying efficiency-34.5%. Drying time-5 hrs	Efficiency-30.2%. Drying time-6hrs	Efficiency-19.3%. Drying time -11 hrs.	Umayal-Sundari and Veeramanipriya (2022)
Solar dryer integrated with STE and PCM used for drying chill	Gravel	The drying time -21 hrs	Drying time -96 hrs	Drying time-150 hrs	Bhardwaj *et al.* (2020)
Convectional solar dryer using TES materials used for drying of *Vitis vinifera*	Sand	The drying time -28	The drying time -53	The drying time -58	Natarajan *et al.* (2017)

2.7 Techno-Economic Analysis the Solar Dryers

The TEA evaluates the technical performance and economic viability of solar drying technologies. This analysis is crucial for understanding the potential benefits and challenges associated with adopting these technologies at different scales (Mahmud *et al.*, 2021). Economic analysis is crucial because it reveals whether the fabricated dryer is commercially viable, affordable, sustainable, and likely to be adopted for further investments (Philip *et al.*, 2022). According to Selvanayaki and Sampathkumar (2017), solar drying technology can be useless if it is not cost-effective, and very few solar drying technologies exist in the market that meet technical and techno-economic aspects.

2.7.1 Overview of Techno-Economic Analysis

The TEA combines technical performance metrics with economic factors to assess the feasibility of solar drying technologies. Key parameters include initial capital costs, operating costs, energy efficiency, drying time, and the quality of dried produces. This analysis helps stakeholders make informed decisions regarding the adoption of solar dryers (Selvanayaki & Sampathkumar, 2017).

2.7.2 Annualized Cost

Economic analysis can be assessed using various methods. One of the method used for assessing solar dryers is the annualized cost method. This is an economic measure used to express the total cost of the investment over its useful life on an annual basis. This measure makes it easier to analyze the long-term financial impact of the investments by distributing the total cost over each year or over the entire life (Philip *et al.,* 2022).

2.7.3 Payback Period

The payback period is the time required for the savings generated by a solar dryer to cover its initial investment. This metric is crucial for farmers and investors considering solar dryers. Studies have shown that the payback period for solar dryers can range from one to five years, depending on factors such as the scale of operation, local climate conditions, and the type of TES materials used (Loemba *et al.*, 2022).

2.7.4 Economic Viability for Small-Scale Farmers

For small-scale farmers, the economic viability of SD depends on several factors, such as the cost of the dryer, availability of financing, and potential market benefits. Subsidies and micro financing options can make solar dryers more accessible to small-scale farmers, enabling them to reduce post-harvest losses and improve income (Lamidi *et al.*, 2019). According to Lamidi *et al.* (2019), rural farmers prefer simple and affordable drying technologies that provide a return on investment. Solar dryers provide small-scale farmers with significant economic benefits, from reducing post-harvest losses and improving product quality to saving costs and creating value-added products. By investing in solar dryers, small-scale farmers can enhance their income stability, market competitiveness, and overall sustainability.

2.8 Life Cycle Assessment of the Solar Dryer

The development and deployment of new technologies can have significant environmental impacts, leading to various forms of pollution. Due this challenge most of the governments and international environments Regulatory organizations are demanding for LCA especially for new emerging technologies for sustainable developments (Guinee *et al.,* 2011). Therefore, the LCA is intending to examine any possible environmental effects caused by the developed solar dryer integrated with TES materials.

2.8.1 Introduction to Life cycle Assessment

According to ISO-14044 (2006), LCA is the process of compiling and analyzing a product system's inputs, outputs, and possible environmental impact from cradle to grave cycle. The LCA is a procedure that is systematic, extensive, and internationally standardized which is used to quantify all pertinent emissions, resource use, environmental and health effects, and resource depletion concerns related to any products or services (WOLF *et al.,* 2010). The goal of conducting a LCA is to provide a comprehensive understanding of the environmental impacts associated with the developed SD, identifying areas for improvement and optimization.

2.8.2 Environmental Impact of Solar Drying Technologies

In the context of solar drying technologies, LCA involves assessing the environmental impacts of these systems throughout their entire life cycle. The assessment helps understand the main source of environmental emissions and possible measures for mitigation. The solar drying technologies can have significant negative impacts as well as positive to the environment. The application of solar drying technology can reduce carbon dioxide (CO_2) and other greenhouse gas emissions compared to other systems (Udomkun *et al.,* 2020), contributing to positive environmental impacts. The environmental impact of different drying methods can be compared using LCA. Solar dryers typically have a lower environmental impact compared to conventional (non-renewable) methods due to their use of renewable energy and lower emissions. However, the production and disposal of TES materials can contribute to environmental impacts, which need to be considered in the LCA (Nayanita *et al.,* 2022). Table 6 compares the carbon footprint of solar drying and conventional drying methods. As it can be seen, the annual CO_2 emission for convection dryers is higher compared to non-convectional (renewable energy) dryers.

Table 6: Carbon footprint of solar drying and conventional drying methods

Type of solar dryer	Solar/Convectional drying	CO_2 emission/ mitigation	Reference
Modified greenhouse dryer used for drying potato chips	Solar dryer	Annual CO_2 emission was 13.45 and 17.6 kg for passive and active mode, Respectively and mitigation of 32.36 tons	Prakash *et al.* (2016)
Indirect cabinet solar dryer for drying various agri-produce	Solar dryer	Annual CO_2 emission was 85.46 kg, and CO_2 mitigation of 391.52 kg	El Hage *et al.* (2018)
Solar greenhouse with biomass back-up heater dryer for coconut drying	Convectional	Annual CO_2 emission was 1518 kg	Ayyappan (2018)
Heat pump dryer for drying various agri-produce	Convection	Annual CO_2 emission was 1818 kg	Fortes *et al.* (2018)

2.8.3 Sustainable Development Goals

Solar dryers contribute to the achievement of several Sustainable Development Goals (SDGs), including eliminating hunger, providing affordable and clean energy, and addressing climate change. By reducing PHIs and improving food security, solar dryers support SDG 2 of zero hunger. Their use of renewable energy aligns with SDG 7 with an objective to ensure clean and reasonably priced energy for everyone (Yousef *et al.*, 2024). Solar drying technologies contribute significantly to several of the United Nations SDGs (Hák *et al.*, 2016). Table 7 shows the summary the alignment of solar drying technologies with SDGs. As it can be seen, solar drying technology is well aligned with SDGs.

Table 7: The alignment of solar drying technologies with SDGs

SDGs	Goal	Contribution of Solar D Technologies
SDG 1	No Poverty	A cost-effective way to pr agricultural produce, solar lowers PHLs and boosts fa income.
SDG 2	Zero Hunger	By preserving food, solar helps ensure food security reduces hunger. It extends the life of agricultural products, m food available during off-seaso
SDG 3	Welfare and Health	Solar drying reduces the ri spoilage and contamin ensuring safer and healthier fo consumption.
SDG 7	Reasonable and sustainable energy	By using renewable solar e solar drying lessens dependen fossil fuels and promotes sustainable agricultural energy
SDG 8	Decent Work and Economic Development	Solar drying technologies cre opportunities in rural areas support sustainable agric practices, contributing to eco growth.
SDG 12	Conscientious Production and Consumption	Solar drying promotes susta consumption and production p by reducing food waste optimizing resource use.
SDG 13	Climate Action	By reducing the carbon fo associated with conventional methods, solar drying su climate action efforts to m climate change.
SDG 15	Life on Land	Because solar drying eliminat need for environmentally dam and land-intensive drying meth contributes to the preservati biodiversity.
SDG 17	Collaborations for the common objectives,	Government, non-government commercial sector collaboratio frequently required for the ad and use of sun drying technol order to assist susta development projects.

2.8.4 Challenges and Opportunities in Life cycle Assessment

While LCA provides the opportunity to understand valuable insights into the environmental impacts of solar dryers, there are challenges in data availability and methodological consistency. Original and secondary data are the two types of LCA data sources. Few research data are derived from original data, according to the research perspective. Most studies rely on secondary data, which is sourced from the Ecoinvent LCA database or from previously published literature(Tan *et al.,* 2023). Table 8 presents the summary of opportunities associated with conducting LCA for SD. Table 9 presents the summary of challenges associated with conducting LCA for solar drying technologies.

Table 8: Summary of the opportunities associated in conducting LCA for solar dyers

S/N	Opportunity	Description
1.	Environmental Benchmarking	LCA can establish benchmarks for the environmental performance of solar drying technologies compared to conventional methods.
2.	Optimization of Designs	Identifying hotspots and inefficiencies through LCA can lead to the optimization of solar drying system designs.
3.	Policy and Decision Support	LCA provides critical data to inform policy-making and support decisions on sustainable agricultural practices.
4.	Market Differentiation	Demonstrating the environmental benefits of solar drying through LCA can enhance market competitiveness and consumer acceptance.
5.	Sustainable Development Goals	LCA can help align solar drying technologies with broader sustainability goals, such as the UN SDGs.
6.	Innovation and Research	Insights from LCA can drive innovation in materials, design, and processes to improve the sustainability of solar drying technologies.
7.	Funding and Investment	Evidence of environmental benefits from LCA can attract funding and investment in sustainable drying technologies.
8.	Public Awareness and Education	LCA results can be used to educate stakeholders about the environmental benefits of solar drying, fostering greater adoption.

Table 9: Challenges associated with conducting LCA for solar dryers

S/N	Challenges	Description
1.	Data Availability and Quality	Limited or inconsistent data on the entire lifecycle of solar drying technologies can hinder accurate LCA.
2.	Complexity of LCA Models	Solar drying systems vary widely in design, scale, and operation, making it difficult to develop standardized LCA models.
3.	Boundary Definition	Determining the system boundaries, including the scope of processes and lifecycle stages to include, can be challenging.
4.	Temporal and Spatial Variability	Variations in solar radiation, climate, and geographical conditions affect the performance and environmental impacts of solar dryers.
5.	Lifecycle Inventory Compilation	Gathering comprehensive and accurate LCI data for all stages, including production, use, and disposal, is complex.
6.	Technical Expertise	Conducting LCA requires specialized knowledge and skills, which may not be readily available in all regions or organizations.
7.	Economic and Social Aspects	Integrating economic and social dimensions into LCA for a holistic sustainability assessment is challenging.
8.	Technological Evolution	Rapid advancements in solar drying technologies necessitate continuous updates to LCA models and data.
9.	Resource Intensity	Conducting thorough LCA studies is resource-intensive, requiring significant time, money, and manpower.

2.9 Summary of Key findings and Identified Gaps in Literature Review

A literature review has revealed post-harvest loss is still posing a threat of food security in developing countries, despite the fact that there has been an effort to reduce PHLs through the application of different interventions. Most of the effort to reduce PHLs has been focused on the farm level where it begins, instead of addressing it at all levels of the food supply chain. This research proposes the application of the appropriate drying technology in every supply chain to combat PHLs. In addition, training on post-harvest management should be provided at all levels.

Traditional drying methods are very essential technologies especially in rural areas with limited financial resources and low electrification rates; however, insufficient research to improve locally adapted technologies and practices limits the effectiveness of locally available technologies. Therefore, more research is needed to improve the performance of traditional drying methods, such as passive solar dryers, that suit a better rural environment.

Thermal energy storage materials play important roles in improving the performance of the solar dryer. While phase change materials offer high precise temperature control, their high costs, complexity and potential for degradation limit their practicality in many solar drying applications. Soapstone, with its cost-effectiveness, durability, environmental friendliness, high thermal conductivity and sustainability, emerges as more suitable materials for thermal energy storage in solar dryers, especially in resource-constrained settings. The choice between these materials ultimately depends on specific applications requirements, budget constraints and long-term performance considerations.

The TEA and LCA are very important studies in providing information on both economic aspects as well as environmental impacts of newly developed technologies. However, based on a literature review, these studies are mostly neglected in most of the research work for the sustainability of the project. Therefore, there is a need to undertake these studies for newly developed technologies. In additional, solar dryer integrated with TES materials are economically viable and environmentally friendly.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Set Up

The SD incorporated with TES materials was manufactured at Arusha Technical College (ATC)-Tanzania and after fabrication works, it was moved to Tanzania Horticultural Association (TAHA) for testing and experiments. The solar dryer comprised of three main parts; drying chamber, solar collectors and energy storage as depicted in Fig. 4-6. All the material for the manufacturing of the solar dryer were sourced from the local market in Arusha City Council.

The primary materials used for fabricating the dryer include 1.5 mm thick mild steel sheets, aluminum sheets of 1.5 mm and 0.5 mm thickness, hollow sections measuring 40 x 25 mm, 6 mm thick clear transparent glass, a 400 mm diameter wind ventilator, 25 x 3 mm flat bars, plastic mesh, gaskets, rivets, bolts, nuts, and soapstone rocks as TES materials. The soapstones were sourced from the Craton geotectonic setting in the Dodoma Region, located in central Tanzania.

To enable application of additional energy sources, like biogas or liquefied petroleum gas (LPG), during periods of severe weather when solar radiation is unavailable, the dryer was equipped with a chamber measuring 2.27 m (L), 1.2 m (W), and 0.5 m (H). A 400 mm diameter wind ventilator was installed at the top of the dryer to facilitate air movement inside and outside the drying chamber. Additionally, a 400 mm diameter wind blower was placed on top of the dryer to further promote air circulation. To optimize solar energy collection throughout the day, three solar collectors, each measuring 1.6 m (L) by 1.2 m (W), were installed. The interior of the solar collectors was coated with black paint to improve the absorption of solar radiation and enhance heat retention.

In order to enable the use of an alternative energy source, such as biogas or liquefied petroleum gas (LPG) gas, in the event of severe weather circumstances when sun radiation is unavailable for drying, the dryer was equipped with a chamber measuring 2.27 m (L), 1.2 m (W), and 0.5 m (H). To facilitate air movement inside and outside the drying chamber, a wind ventilator with a diameter of 400 mm was installed at the top of the dyer. On top of the dyer, a 400 mm diameter wind blower was installed to allow air to circulate both inside and outside the drying chamber. To make it easier to gather solar energy throughout the day, three solar collectors measuring 1.6 m (L) by 1.2 m (W) were supplied. The solar collector's interior was painted black, which allowed it to absorb solar radiation and hold onto heat energy.

The size of natural rock materials used as thermal storage in a solar dryer significantly impacts the performance of the dryer. Larger rocks have a greater volume, allowing them to store more heat energy. However, they may take longer to heat up due to their larger thermal mass, which can delay the start of the drying process. Smaller rocks heat up more quickly because they have a larger surface area relative to their volume. This allows them to absorb solar energy faster and reach higher temperatures earlier, but they store less heat overall compared to larger rocks (Lasheen *et al.*, 2023). In this case, the soapstone rocks were reduced to small size in order to improve storage performance. The soapstones were placed 0.12 m above the base of the solar collector and covered with a 0.5 mm-thick aluminum plate coated in black paint using tar for efficient solar radiation absorption. The weight of the soapstone inside each solar collector, as shown in Fig. 12, was measured with a scale and found to be 220 kg per collector. An air vent, 0.08 m deep and 1.2 m wide, featuring an adjustable gate to control airflow, was situated between the absorber plate and the collector glass.

The air vent design followed the recommendations of Raju *et al.* (2013), who suggested a minimum 5 cm vent for hot climates. The top of the solar collector was covered with a 6 mm clear glass panel to allow solar radiation to enter. The tilt angle of the solar collector, set to capture an optimal amount of solar radiation, was determined to be 13.4° according to Missana and Mashingo (2022). Figure 10 and 11 display photographs of the constructed solar dryer, while Fig. 12 provides its schematic diagram. A summary of the solar dryer's specifications can be found in Table 10.

Table 10: Summary of the specifications of the solar dryer

S/N	Descriptions	Unit	Value
1.	The drying chamber's volume	m^3	3.96
2.	The solar collector glass's thickness	m	0.006
3.	The aluminum absorber plate's thickness	mm	0.5
4.	Thickness of fiberglass (Insulation)	m	0.025
5.	Solar dryer's loading capacity	kg	50
6.	The solar collector's surface area	m^2	1.8
7.	The collector's volume filled with TES materials	m^3	0.18
8.	Depth of air vent	cm	0-8
9.	The soapstone weight in each collector	kg	220
10.	The tray's surface area	m^2	0.65
11.	The tray loading capacity	kg	4
12.	The separation between the trays	m	0.24
13.	The collector's tilt angle		13°.4

Figure 10: Photography of the developed solar dryer integrated with TES materials

Figure 11: Photography of the solar dryer collectors with and without TES materials

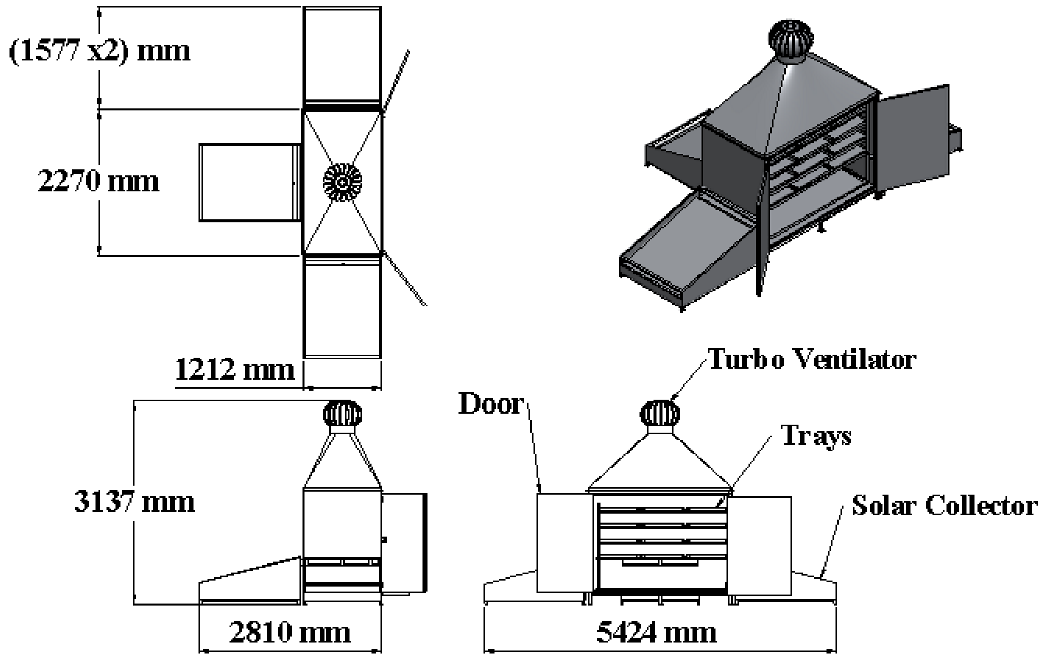

Figure 12: Schematic diagram of the development solar dryer

3.2 Experimental Procedure

The experiments were carried out at the TAHA Farmers Training Centre in Tengeru, located in the Arusha Region of Tanzania. The SD was evaluated by drying pineapples (Ananas comosus) and carrots (Daucus carota), which are crucial products for Tanzania's economy and nutrition. However, normally affected by PHLs, in particular during harvesting seasons. A simple hand slicer was used to cut carrots into circular slices with an average diameter of 2.6 cm and an average weight of 3 g. Pineapples were cut lengthwise into four sections, with each section manually sliced. The samples underwent no pre-treatment. A total of 50 kg of freshly sliced produce was dried using the SD and under open sun until the final moisture content was below 10% on a wet basis (wb). The fresh samples, purchased from the local market in the Arusha Region, Tanzania, had an average weight of 6.5 g per carrot and 1.5 kg per pineapple. After washing, the samples were peeled and sliced into uniform 3 mm thick pieces.

Drying time, solar radiation, weight reduction, relative humidity as well as temperature were recorded after every 30 minutes. Within the soapstone compartment, three SSN-11E USB temperature data logger probes were installed to monitor the soapstone's temperature. To track temperature and relative humidity, SSN-22E USB temperature and humidity data logger meters were located at the outlet and inlet of the solar collectors. Additionally, three similar data logger meters were installed within the drying chamber to measure its relative humidity and temperature. A Kestrel 3000 wind meter was employed to measure the airflow inside and outside the drying chamber, while an FF1976 constant digital weighing scale was used to record the weight of the products. Solar irradiance was measured with a TES 132 Solar Power Meter, placed on the solar collector. The drying experiments were conducted in two operational modes: One with the solar dryer operating without TES materials and the other with TES materials integrated into the solar dryer. Data were collected over three consecutive days for each mode, and average values were calculated. The standard deviation for temperature and humidity measurements was determined using an Excel spreadsheet. The data collection period spanned from January to March 2023.

3.3 Performance Analysis

The performance evaluation of the solar dryer incorporated with soapstone as a TES material involved measuring several key parameters. These included the sensible heat energy storage capacity of the TES material (E), its storage efficiency (η_s), the amount of water removed from the product (M_t), the drying rate (D_r), thermal efficiency (η_t), collector efficiency (η_c), and the percentage reduction in drying time. Additionally, a comparative assessment was carried out to analyze drying time, temperature, and relative humidity under three different conditions: using TES materials, without TES materials, and OSD.

3.3.1 Amount of Sensible Heat Energy Storage

The energy storage capacity of materials is a crucial factor in selecting thermal energy storage materials, as it indicates the quantity of heat energy that can be stored in the materials at any given moment. The amount of energy storage was estimated by using Equation (1) according to Cetina-Quiñones *et al.* (2021).

$$E = M_a C_p (T_f - T_i) \quad (1)$$

Where; E=Energy storage (J)

M_a=Weight of storage materials (Kg)

C_p=Specific heat capacity of soapstone (J /kg ^oC)

T_i=Temperature of the storage materials at time t (^oC)

T_f=Temperature of the storage material in the proceeding time (^oC)

3.3.2 Storage Efficiency

The storage efficiency of TES materials (η_s) is the ration of the discharged energy to the charging energy from the TES materials. It was calculated by using Equation 2 according to Cetina-Quiñones *et al.* (2021).

$$(\eta_s) = \frac{E_{discharge}}{E_{charge}} \quad (2)$$

3.3.3 Weight of Water Evaporated

The weight of water removed refers to the quantity of moisture lost from the product during the drying process. Fruits and vegetables typically contain a significantly higher water content compared to their solid components. This value was determined using Equation (3), as outlined by Fudholi *et al.* (2015), Santanu-Malakar (2018) and Suleiman *et al.* (2023).

$$M_w = \frac{M_o(M_i - M_f)}{100 - M_f} \quad (3)$$

Where; M_o = Initial weight of the sample

M_i = Initial moisture content of the sample on the wet basis (%)

M_f =Final moisture content of the sample on wet basis (%)

3.3.4 Drying Rate

The drying rate is defined as the ratio of moisture evaporated from the product to the time taken for evaporation. The drying rate of the products was calculated using Equation (4) as according to Hasibuan *et al.* (2020)

$$DR = \frac{M_w}{t} \quad (4)$$

Where; M_w =Total mass of water evaporated from the drying products (kg)

t = Drying time (hours)

3.3.5 Dryer Thermal Efficiency

This the ratio of the useful energy utilized for moisture evaporation to the total energy input supplied to the drying system. It is expressed as a percentage and indicates how effectively the dryer converts energy into useful heat for the drying process. This was found by using Equation (5), as suggested by Ayyappan *et al.* (2016).

$$\eta_t = \frac{M_w h_{fg}}{A_c * I} \quad (5)$$

Where; M_w is the total weight of water lost from the drying products (kg), h_{fg} is the latent heat of vaporization of water (kJ/kg), A_c is the area of the solar dyer (m^2), I is the solar irradiance (W/m^2).

3.3.6 Collector Efficiency

Collector efficiency refers to the ratio of the useful heat absorbed per unit of aperture area to the average incident radiation on the collector. The efficiency of the collector with energy storage (η_x) was calculated using Equations 6 and 7, as outlined by Singh *et al.* (2018).

$$(\eta_c) = \frac{M_a c_a (T_{c-} T_a)}{A_c I} \qquad (6)$$

Where; M_a=Mass of air flowing in the collector per unit time (kg/s)

C_a =Specific heat capacity of air ($kJkg^{-1}K^{-1}$)

A_c=Collector area (m^2)

I = solar irradiance (W/m^2)

The mass of air flowing in the collector per unit time (M_a) was calculated by using Equation 7 according to Singh *et al.* (2018).

$$M_a = \rho_a V_a C_v \qquad (7)$$

Where; V_a= Velocity of air (m/s)

ρ_a=Density of air (m^3/kg)

C_v = Cross section area of air vent (m^2)

3.3.7 Saving in Drying Time

The percentage of drying time saved is calculated by comparing the drying time achieved with the solar dryer to that of OSD. It was calculated using equation 8, according to Fudholi *et al.* (2013).

$$\text{Saving in drying time (\%)} = \frac{t_{OS} - t_{SD}}{t_{OS}} \qquad (8)$$

Where: t_{OS} =time taken in (hrs) to dry product on OSD

t_{SD} = time taken in (hrs) to dry product in developed solar dryer

3.4 Proximate of the Dried Products

Although drying is a crucial process for food preservation, it has been noted to diminish the quality of dried products in terms of color, flavor, and nutrients (DG, 2014; Gunathilake *et al.*, 2018; Mongi & Ngoma, 2022). However, according to Bhardwaj *et al.* (2020), reported that using thermal energy storage (TES) for drying helps retain nutritional values. To assess potential losses in nutritional composition, proximate analysis was performed on the dried products. This evaluation focused on pineapples and carrots, examining various parameters such as moisture content, ash content, crude fiber, fat content, protein, vitamins, and minerals.

3.4.1 Determination of Moisture Content

Determining moisture content is essential for understanding the water level present in the product before and after drying. The moisture content was measured using the gravimetric oven drying method, following the protocols established by the Association of Official Analytical Chemists (AOAC) methods (Nielsen, 2017). A precisely weighed 5 g sample of paste was placed in a clean, dry petri dish and then dried in an oven at 105°C for 24 hours, or until there was no further change in weight. The petri dish was then placed in a desiccator for 30 minutes to cool. After cooling, the final weight was recorded, and the moisture percentage was calculated using Equation 9.

$$\%\ \text{Moisture contents (On wet basis)} = \frac{M_i - M_f}{M_i} \times 100 \qquad (9)$$

M_i is the initial weight of the sample (wet weight)
M_f is the final weight of the sample (dry weight)

3.4.2 Determination of Ash Contents

Ash content determination is the first step in preparing samples for specific analyses. The dry ashing method was used, in accordance with the procedures outlined by (AOAC) methods (Nielsen, 2017). A clean, empty crucible was placed in a muffle furnace at 550°C for one hour to ensure that any impurities on its surface were completely burned off. Afterward, the crucible was cooled in a desiccator for 30 minutes, and its weight was recorded. Exactly 5 g of the sample was then added to the crucible, which was subsequently placed back in the muffle furnace. The final weight was measured after the crucible and its contents had been heated in the furnace for 24 hours and cooled in the desiccator. The percentage of ash content was calculated using Equation 10.

$$\%\ \text{Ash content} = \frac{\text{Weight of ash}}{\text{Weight of sample}} \times 100 \qquad (10)$$

3.4.3 Determination of Crude Fiber

The analysis of crude fiber involves two stages of digestion using acid and alkaline solutions, following the method outlined by (AOAC) methods (Nielsen, 2017). A known weight of the sample 5 grams was placed in a round-bottom flask and boiled with dilute sulfuric acid solution. The acid-treated sample was then treated with an alkaline solution. The residue left after both digestions was dried at a temperature of 105°C until a constant weight is reached. The percentage of fiber was calculated using Equation 11.

$$\text{Crude fiber (\%)} = \frac{\text{Weight of residual} - \text{Weight of ash}}{\text{Weight of sample}} \times 100 \quad (11)$$

3.4.4 Determination of Protein

Protein is an essential nutrient for the body, providing crucial elements such as amino acids necessary for the growth and maintenance of cells and tissues. However, when agricultural products are dried, particularly at high temperatures, they may lose some nutrients (Dos Santos *et al.*, 2015; Olusola, 2009; Timm *et al.*, 2020). The protein concentration was evaluated using the Kjeldahl nitrogen method, as outlined in the (AOAC) methods (Nielsen, 2017). In this process, exactly 5 g of the sample was digested by heating with concentrated sulfuric acid in the presence of a Kjeldahl catalyst, converting it to ammonium sulfate. The digested mixture was then made alkaline with sodium hydroxide (NaOH). The amount of ammonia nitrogen was quantified through titration with hydrochloric acid (HCl) solution. The percentage of nitrogen content was calculated using Equation 12. To determine the protein content, the nitrogen value was multiplied by a conversion factor of 6.25, as shown in Equation 13.

$$\text{Nitrogen (\%, w/W)} = \frac{\text{Volume of acid (ml) x Molarityof acid (moll}^{-1}\text{) x 14(gmol}^{-1}\text{)}}{\text{Weight of smaple (g) x 100}} \quad (12)$$

$$\text{Protein (\%)} = \text{Nitrogen (\%, w/W)} \ \text{x Protein Factor} \quad (13)$$

3.4.5 Determination of Fats

Fat content was determined using the Soxhlet method as described in the AOAC methods (Nielsen, 2017). A 5-gram sample was placed in a thimble, which was then positioned in a Soxhlet extraction system. To the extraction flask, 70 ml of petroleum ether was added. The solvent was heated in the flask, causing its vapors to ascend to the condenser, where they were cooled and returned to liquid form. This liquid solvent then flowed into the thimble, extracting the fat from the sample. Once the extraction was complete, the solvent was removed from the fat using a rotary evaporator or gentle heat. The extracted fat was then weighed after being dried to eliminate any remaining solvent. The fat content percentage was calculated using Equation 14.

$$\% \text{ Fats} = \frac{\text{Weight of crude fat}}{\text{Weight of Sample}} \text{x}100 \qquad 14$$

3.4.6 Determination of Total Carbohydrates

The total carbohydrate content was calculated by deducting the weight of non-carbohydrate components from the original weight of the sample, as illustrated in Equation 15

Total carbohydrate = Initial Sample Weight− (Weight of Fat Weight of Protein Weight of Moisture Weight of Ash contents Weight of Crude fiber) 15

3.4.7 Determination of Minerals

Fruits and vegetables are rich sources of essential minerals that support various physiological functions, including bone strength, muscle development, and brain activity. In this study, mineral analysis was performed using Atomic Absorption Spectroscopy. The sample was first dried to remove moisture and then subjected to a muffle furnace at around 500°C to burn off organic matter, leaving only the mineral ash. To dissolve the ash and prepare it for analysis, 10 ml of nitric acid (HNO_3) was added. The resulting solution was then examined using the Atomic Absorption Spectroscopy technique to determine the mineral composition.

3.4.8 Determination of Vitamin

The determination of vitamins in the sample was conducted following the AOAC methods (Nielsen, 2017), using High-Performance Liquid Chromatography. In this process, vitamin A was extracted with an organic solvent, while vitamin C was extracted using an acidic solution to ensure efficient separation and analysis.

3.5 Techno-Economic Analysis

The purpose of conducting a TEA was to assess the technical feasibility and economic viability of a solar dryer incorporated with TES materials. By combining technical and economic evaluations, TEA provides valuable insights that aid decision-makers, investors, and stakeholders in making informed decisions regarding the adoption and scalability of the developed technology. Some assumptions were parameters for evaluation of economic analysis of the dryer. These includes; the solar dryer lasts after 20 years of operation as reported by

Prakash *et al.* (2017) for most of the solar dyer. Inflation rates of 4.8 % was adopted from monthly economic review report from Bank of Tanzania (2023). Further, the 7% annual interest rate stated by Aly *et al.* (2019) was adopted. Since the dyer was made from mild steel and aluminum which are durable materials. The maintenance cost and salvage value were considered to be 5% of the annualized capital cost, as utilized in the study by Philip *et al.* (2022). Table 11 shows summary of the important assumptions made during analysis.

Table 11: Summary of the parameters used in economic analysis

S/N	Parameters	Value
1	Capital cost	$ 5430.9
2	Maintenance cost	5% of annualized capital cost
3	Salvage value	5% of annualized capital cost
4	Inflation rate (i)	4.8 %
5	Dryer life span (n)	20 years
6	Cost of fresh pineapple	$ 0.25/kg
7	Selling price of the dried pineapple	$ 4 /kg
8	Cost of fresh carrots	$ 0.2/kg
9	Selling price of the dried Carrots	$ 3 /kg
10	Interest rate (d)	7 %
11	Number of days of operation per year (D)	250 days
12	Dryer drying capacity	50 kg/day (1batch)

3.5.1 Annualized Cost

Annualized cost refers to the total cost of an investment or project distributed evenly over its useful lifespan. The annualized cost was calculated according to Philip *et al.* (2022) by using Equation 16.

$$C_a = C_{ac} + C_m - V_s + C_{rf} + C_{re} \qquad (16)$$

Where, C_a =Annualized cost of the dryer (USD)

C_{ac}= Annualized capital cost (USD)

C_m= Annualized maintenance cost (USD)

V_s= Annualized salvage value (USD)

C_{rf}= Running fuel cost (USD) is zero because the passive dryer does not fuel.

C_{re}= Cost of electricity (USD) is zero because the dryer does not use electricity.

$$C_{ac} = C_{cc}F_c \qquad (17)$$

Where, C_{cc}=Capital cost of the dryer (USD)

F_c=Capital recovery factor

$$V_s = VF_s \quad (18)$$

Where, V=Salvage value (USD)

F_s=Salvage fund factor

$$F_c = \frac{d(1+d)^n}{(1+d)^n - 1} \quad (19)$$

$$F_s = \frac{d}{(1+d)^n - 1} \quad (20)$$

Where, d=Interest rate

n=Lifespan of solar dryer

Weight (kg) of the dried product in the dryer is given according by Equation 21 according to Philip *et al.* (2022).

$$M_y = \frac{DM_d}{D_b} \quad (21)$$

Where, D=Number of drying days in a year

M_d=Weight (kg) of dried product removed from the dryer per batch

D_b=Number of days for drying one batch of the product

The Cost for drying 1 kg of the dried products (C_s) is given by Equation 22 according to Philip *et al.* (2022).

$$C_s = \frac{C_a}{M_y} \quad (22)$$

3.5.2 The Life Cycle Savings

Life Cycle Savings (Lcs) is a financial metric used to evaluate the cost-effectiveness of a system over its entire lifespan. This evaluation helps determine whether the investment in a new technology results in significant financial benefits over time (Philip *et al.*, 2022). Cost of fresh product per kilogram of dried product was calculated using Equation 23 according to Chavan and Thorat (2021). This comparison is crucial since, throughout the drying process, fresh products lose a large percentage of their weight owing to water loss. Therefore, more fresh product is needed to make 1 kilogram of dried product.

$$C_{dp} = C_{fp} \times \frac{M_f}{M_d} \qquad (23)$$

Where, C_{fp} =Cost of fresh product (USD/kg)

M_f=Weight of fresh product (kg)

The total cost of drying 1 kg of the product (C_{ds})is given by summation of the total cost of fresh product (C_{dp}) and the cost required to dry 1 kg of the product (C_s) was calculated by using Equation 24 according to Chavan and Thorat (2021).

$$C_{ds} = C_{dp} + C_s \qquad (24)$$

Considering the dried products by dryer for this particular project are to be branded, the savings per kilogram of the dried product (S_{kg}) in annual basis is expressed in Equation 25 according to Prakash *et al.* (2017).

$$S_{kg} = C_b - C_{ds} \qquad (25)$$

Where, C_{ds} =Total cost of fresh product

C_b=Selling price of 1 kg of dried product (USD)

Batch wise savings (S_b) on drying days is expressed in Equation 26 according to *Prakash et al.* (2017).

$$S_b = S_{kg} \times M_d \qquad (26)$$

S_{kg}= The savings per kilogram of the dried products in annual basis

Daily wise savings (S_d) on drying days is expressed in Equation 27 according to Prakash *et al.* (2017).

$$S_d = \frac{S_b}{D_b} \qquad (27)$$

D_b=Number of days for drying one batch of the product

3.5.3 Annual Saving's Present Worth

Year wise savings of the drying products (S_j)under study in n^{th} year is expressed in Equation 28 as proposed in Prakash *et al.* (2017).

$$S_n = S_d x D x (1 + i)^{n-1} \qquad (28)$$

Where, I =Inflation rate (%)

F_{pn} x S_nD=Number of drying days in a year

S_d=Saving per day (USD

The present worth of savings in n^th^ year is given by Equation 29 according to Prakash *et al.* (2017).

$$P_n = F_{pn} \times S_n \quad (29)$$

Where, F_{pn}=Present worth factor for n^th^ year (USD)

S_n=Yearly savings for drying product in n^th^ year (USD)

The present worth factor for n^th^ year is given by Equation 30 according to Prakash *et al.* (2017).

$$F_{pn} = \frac{d}{(1+d)^n} \quad (30)$$

Where, d= Interest rate and n = number of years

Life cycle savings is found by summation of yearly savings of present worth over life span of the dryer.

3.5.4 Payback Period

The payback period (PP) is a key financial measure that calculates the time it takes for an investment to recover its initial cost through accumulated savings or revenue (Prakash & Kumar, 2020). Payback period (PP) was calculated by using Equation (31) according to Prakash *et al.* (2017).

$$PP = \frac{\ln(1 - \frac{C_{cc}}{S_1}(d-i)}{\ln\left(\frac{1+i}{1+d}\right)} \quad (31)$$

Where, d= Annual interest rate =7 %

i = Inflation rate=4.8 %

S_1= Savings during first year

C_{cc}=Capital investment cost of the dryer (USD)

3.6 Life Cycle Assessment

The LCA methodology consists of four phases, as defined in ISO-14040 (2006), which outlines the principles and framework and ISO-14044 (2006) which specifies the requirements and guidelines. These phases are: defining the goal and scope, conducting inventory analysis, assessing the environmental impacts, and interpreting the results.

3.6.1 The Goal and Scope Definition

The goal for conducting LCA for solar dryer incorporated with TES materials is to analyse the environment impacts caused by solar dryer incorporated with TES materials for drying of food products. The scope of the work includes; raw materials extraction, transportation and manufacturing of the dryer. Dryer operation and recycling were not considered in this study, because the developed solar dryer rely on solar energy for drying which is considered clean as clean energy. The material extractions includes all the material manufacturing process. The dryer fabrication process includes the metal cutting, folding/bending, welding, drilling, grinding and painting. Transportation includes movement the materials from the neighbourhood local market to the workshop for fabrication. Some of the techniques used to control environmental pollution during fabrication includes; optimization of materials fabrication and processes such as cutting and welding in order to reduce material waste, use of dusty bin for storage of waste materials, optimization of voltage, current, and welding to minimize the production of fumes and gases, ensuring proper airflow in the welding area to dilute and remove airborne contaminants.

The functional unit is the environmental impacts caused by materials extraction and fabrication of the solar dryer. Figure 13 shows the system boundaries for LCA which includes inputs of the materials and outputs of the wastes produced. The inputs are raw materials and solar energy whereas the output solid wastes from manufacturing process and recycling and emission of gases to the air during manufacturing (welding).

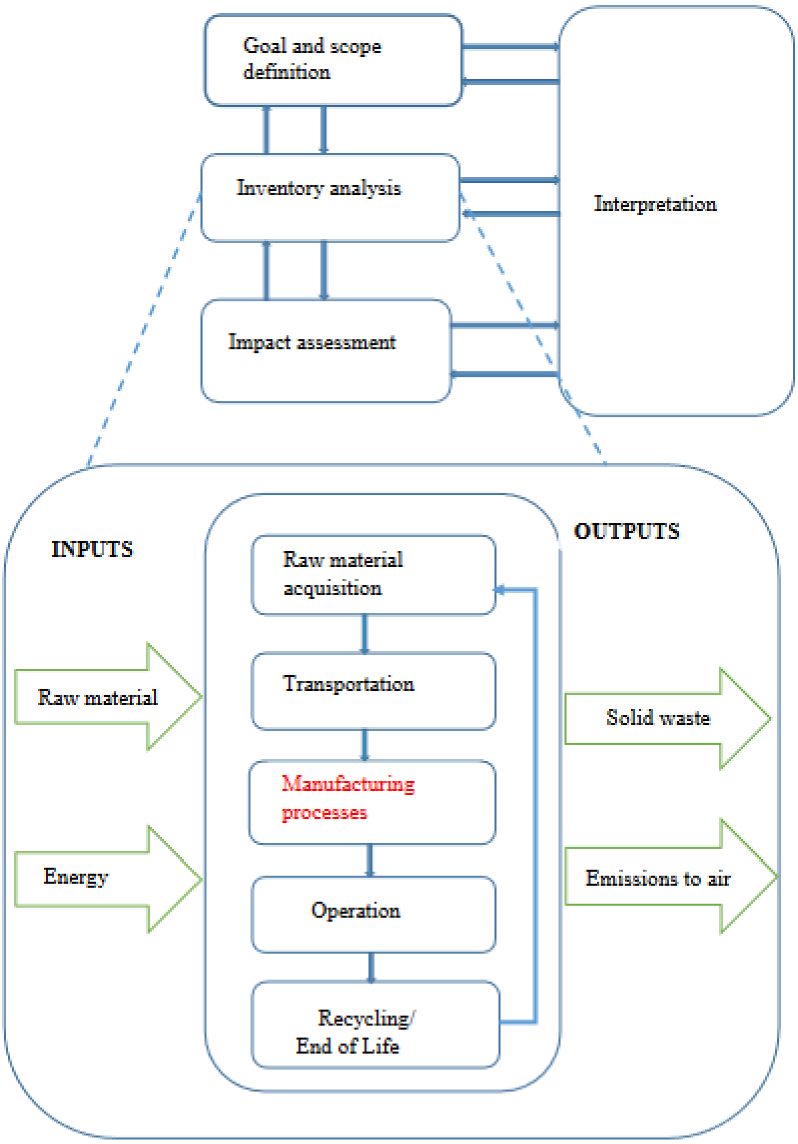

Figure 13: The four interactive phases and boundaries of life cycle assessment

3.6.2 Life Cycle Inventory

The inventory analysis is used to describe the input and output of the products. The materials used for construction of the dryer are mild steel, aluminium sheet, glasses, and insulation materials and paints. The inventory of the materials and their respective weight used for fabrication of solar dyer is depicted in Table 1. The fabrication process included cutting, bending, welding and gridding. All these fabrication process can contribute to environmental effects. It was assumed that the recycled materials are 70% of the total material used as adopted by Nayanita *et al.* (2022). Recycling has been considered for all types of materials except glass, paints and insulation materials as they cannot be recycled. Tables 12 and 13 shows the inventory of the materials considered in the analysis of the LCA and fabrication processes.

Table 12: Inventory of the materials used for fabrication of the solar dryer

S/N	Materials	Unit	Weight
1	Mild steel	kg	806
2	Aluminum	kg	240
3	Flat glass, uncoated	kg	65
4	Insulation spiral-seam duct, rock wood	m	48
5	Alkyd paint	kg	20

Table 13: Process considered for LCA assessment

S/N	Materials	Unit	Weight
1	Welding, arc, steel	m	10
2	Steel drilling	kg	2
3	Aluminum drilling	kg	1
4	Transport, freight, lorry 3.5-7.5 metric ton	km	5

3.6.3 Life cycle Impact Assessment

Simapro 9.5.0.0, integrated with the ReCiPe 2016 Midpoint and Endpoint global method, was used for the analysis. The ReCiPe 2016 offers characterization factors that are representative of a global scale, and not limited to the European scale. The used materials during fabrication and their emissions are translated to environmental impacts. The lifecycle Impact Assessment (LCIA) helps in interpretation of emissions from resources extraction into a specific number of environmental impact score and this is done by characterization factor which indicates the environmental per unit of stressor (Huijbregts *et al.,* 2017). In this study both midpoint (problem-oriented) and endpoint characterization were used. The 18 midpoint category used includes; global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation ozone, formation (terrestrial ecosystem), terrestrial acidification, fresh water eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogen toxicity, human non- carcinogen toxicity, land use, mineral resources scarcity, fossil resources scarcity, water consumption. The endpoint (damage oriented) method was used for damage assessment in three category indicators; human health, ecosystem quality (natural environment) and resources scarcity.

3.6.4 Interpretation

The interpretation was used to withdrawn final conclusions of the research work.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Evaluation of Drying Parameters

The performance of a solar dryer is influenced by variations in solar radiation reaching the ground surface. Figure 14 illustrates significant fluctuations in solar energy intensity over time with standard variation. The standard deviations were varying from 1-30 W/m^2. The average sun irradiation levels varied, with minimum values around 160 W/m^2 and maximum values reaching up to 1140 W/m^2. Lower irradiation levels were recorded in the morning and evening, while peak levels occurred around 1:00 pm. The intensity of solar energy input fluctuates significantly over time, likely due to the prevalence of diffuse radiation and cloud cover typical of equatorial regions as noted by Yang *et al.* (2012) in their study on estimating hourly solar irradiance with cloud cover index. However, integrating TES materials within the collectors helps to mitigate these energy variations caused by changing solar irradiance levels.

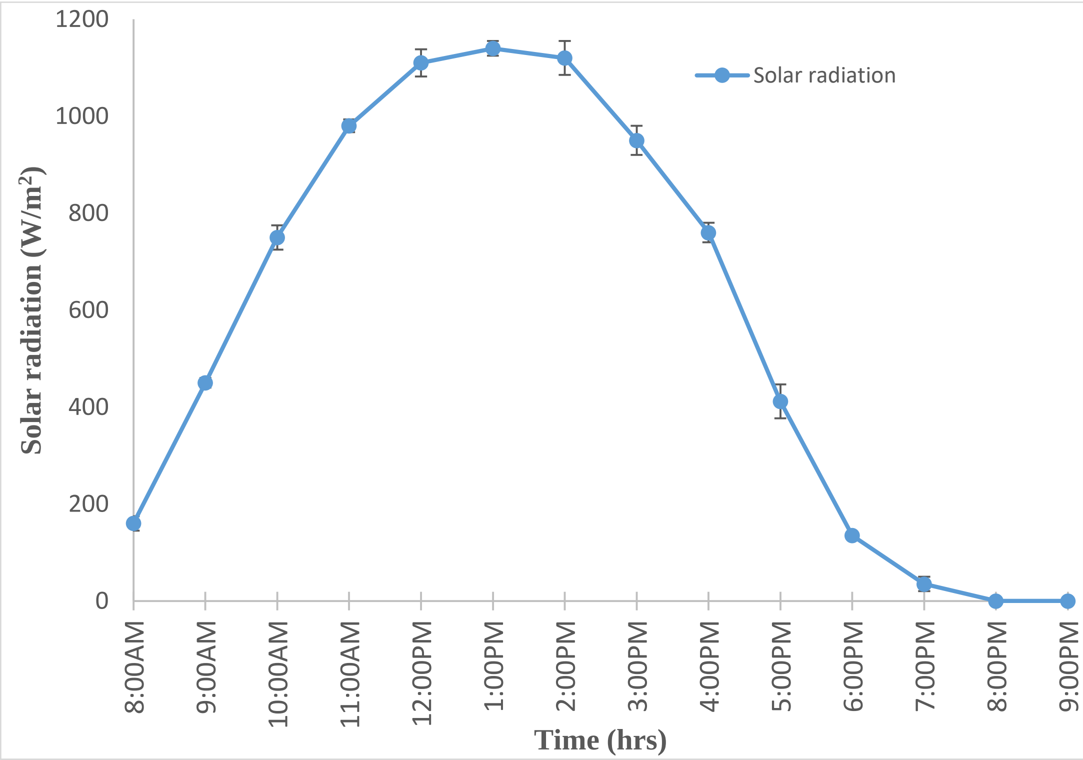

Figure 14: Variations of solar radiation with time and standard deviation

Temperature is very essential during drying process. Figure 15 compares the temperature variations within the drying chamber under three conditions: With TES integration, without TES materials, and ambient temperature.

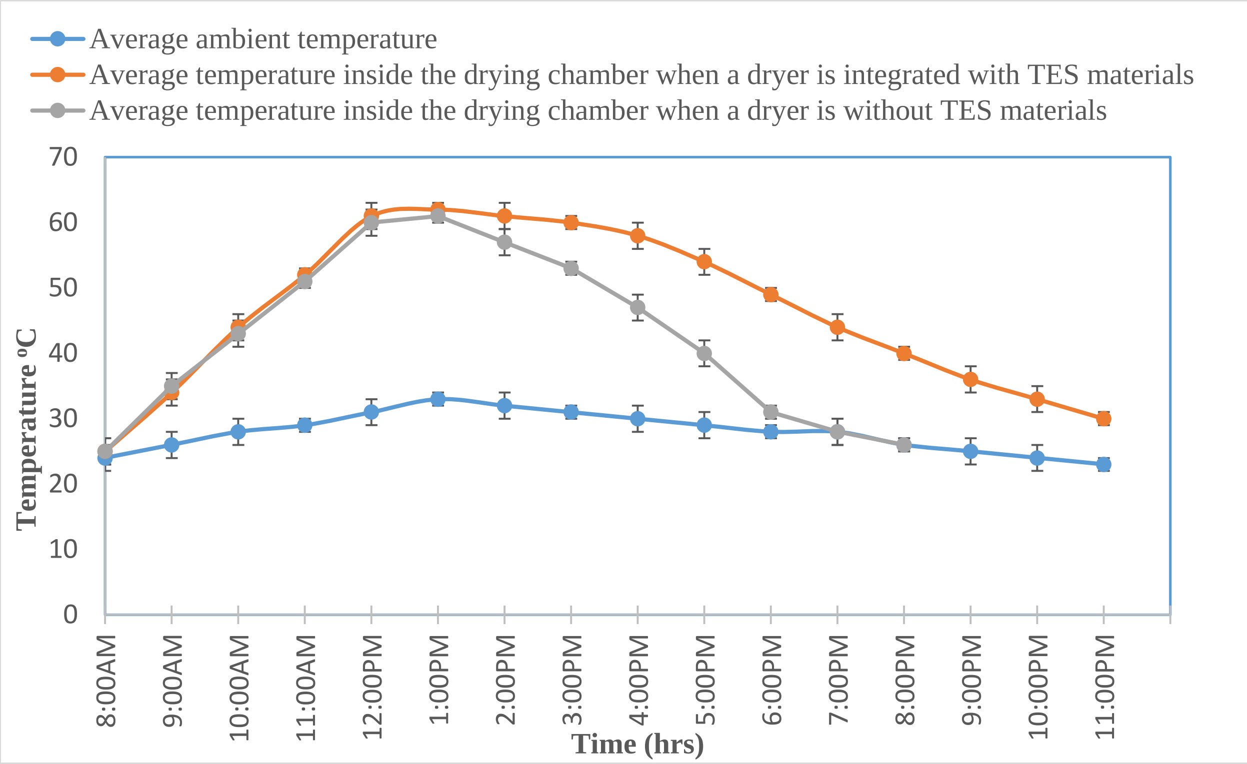

Figure 15: Variations of temperatures with time

This comparison highlights the impact of TES on stabilizing internal temperatures in the drying chamber. The standard deviations for temperatures were varying from 1-2^{o}C. The highest temperature was recorded at 1:00 pm, coinciding with peak solar irradiance. At this time, the dryer with TES materials reached a maximum temperature of 62°C, while the dryer without TES materials recorded 61°C. In contrast, the ambient temperature peaked at 33°C. As air flows through the solar collectors, its temperature rises, resulting in a higher temperature inside the drying chamber compared to the ambient temperature. This observation is in agreement with previous studies reported by Behera *et al.* (2019), who designed and fabricated forced convection cabinet type of solar dryer for drying fruits and vegetables.

The temperature analysis was conducted for atmospheric temperature, inlet collector temperature, glass plate temperature, absorber plate temperature and outlet collector temperature. The results showed that the ambient temperature was lowest ranging 32-40.5^{o}C, inlet collector temperature was ranging 40.1-52^{o}C, glass plate temperature was ranging 42-50^{o}C, outlet collector temperature was ranging 58-62.4^{o}C and the maximum temperature was observed at absorber plate temperature ranging 78-87^{o}C. In the same study of temperature analysis between ambient temperature, tray's temperature and outlet drying chamber temperature, the results showed that the ambient temperature was less than outlet drying chamber temperature followed by tray's temperature.

The performance of a passive solar dryer was experimentally investigated in another work by Dasin *et al.* (2015). Temperature comparisons between the product, drying chamber, ambient, and collector temperatures were evaluated. The results showed that the ambient temperature lowest ranging 27-29^{o}C, followed by drying chamber temperature which was ranging 39-41^{o}C, and the maximum temperature was collector temperature which was ranging 55-60^{o}C. Furthermore, Abuelnuor-Abuelnuor *et al*. (2021), used a solar drier equipped with reflectors and phase-change material to conduct an experimental investigation on tomato drying. The temperature analysis was conducted for collector inlet temperature, tray's temperature, chamber outlet temperature and absorber plate temperature. The results revealed that temperature at collector inlet was the lowest value ranging 42-48^{o}C, tray's temperature ranging 42-56^{o}C, chamber outlet temperature ranging 48-58^{o}C, and the absorber plate temperature ranging 49-58^{o}C.

The use of TES materials helped maintain a consistently higher and more stable temperature in the drying chamber compared to a system without TES materials. For instance, at 7:00 pm, when the ambient temperature was 28°C, the temperature inside the drying chamber with TES materials was 44°C. This temperature then gradually decreased until 12:00 am, when the drying chamber temperature reached 27°C while the ambient temperature was 23°C. The incorporation of TES materials extended the drying temperature for approximately 3-4 hours beyond sunset. Thus, soapstone materials are crucial for storing solar energy during the day and gradually releasing it, which effectively extends the drying time. The findings are consistent with those of Bhardwaj *et al.* (2020), who assessed the performance of a solar dryer integrated with a combination of SHS and PCM for drying chilies. Their study reported that ambient temperatures ranged from 22°C to 30°C, while the temperature of the collector without TES materials varied between 22°C and 46°C. In contrast, the collector with TES materials achieved temperatures ranging from 25°C to 65°C. Additionally, they noted that the use of SHS provided a backup of 2-3 hours after sunset, and the dryer with TES materials achieved the shortest drying time, reaching a saturation level of 4.85% (wet basis) compared to drying conducted without TES and natural sun drying methods.

Relative humidity is another crucial factor in the product drying process. Figure 16 presents a comparative analysis of the changes in air relative humidity within the drying chamber for both the dryer with TES materials and the one without, along with the ambient conditions over time. The standard deviations for temperatures were varying from 1-3 %.

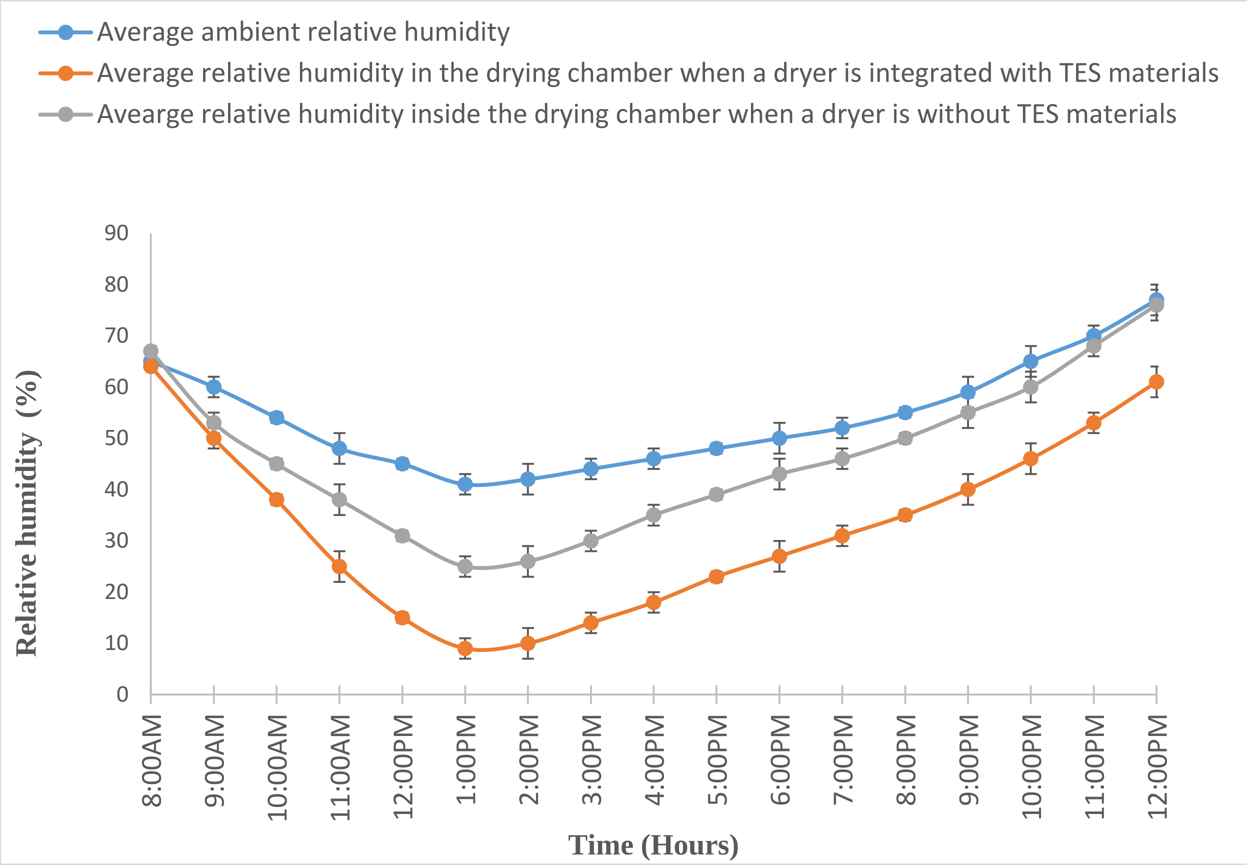

Figure 16: Variations of relative humidity with time

The data shows a clear difference in relative humidity levels between the drying chambers with and without TES materials. The drying chamber with TES materials consistently maintains a lower relative humidity compared to the one without. This suggests that TES materials contribute to more effective moisture regulation. Ambient relative humidity varied, ranging from 41% during the day to 77% at night. The lowest relative humidity across all methods occurred around 1:00 pm, with the highest recorded at 12:00 am. In the chamber without TES materials, the relative humidity was around 25% during the day and 76% at night, while in the chamber with TES materials, it was approximately 9% during the day and 55% at night. This indicates that the use of TES materials results in a significant reduction in relative humidity inside the drying chamber. The lower humidity is likely due to the TES materials' ability to maintain higher temperatures, which in turn reduces moisture content in the air.

These results align with the findings of Cetina-Quiñones *et al.* (2021), who conducted an experimental evaluation of an indirect solar dryer integrated with sensible heat storage materials. Their study reported that the inclusion of storage materials elevated the drying temperature and reduced relative humidity.

The incorporation of TES materials entails charging thermal storage materials when solar energy is accessible and discharging them when it is not. The thermal energy stored in the soapstone during the charging process was calculated using Equation (1) and found to be 8.8 MJ, while the energy discharged was 6.5 MJ. During the day, when solar energy is available, the solar collectors absorb and store energy (charging) in the rock materials amounting to 8.8 MJ. After sunset, the solar collectors release (discharging) the stored energy from the rock materials into the drying chamber to enable the continued drying process. In addition, the discrepancy between charging and discharging energy values (8.8 MJ vs. 6.5 MJ) is due to thermal losses that occur during the storage and discharge processes. For instance, insulation losses, ambient heat dissipation, and inefficiencies within the TES system might lead to less energy being available during discharge. The storage efficiency, calculated using Equation (2), was determined to be 74.5%. The results obtained are in strong agreement with those reported by Cetina-Quiñones *et al.* (2021), who conducted an experimental evaluation of an indirect solar dryer for agricultural products using limestone and beach sand as TES materials. They found that the charging and discharging energy for limestone was 2.4 MJ and 2.0 MJ, respectively. For beach sand, the charging energy was 5.9 MJ, while the discharging energy was 4.1 MJ. The storage efficiency was 84.2% for limestone and 70.3% for beach sand.

4.2 Performance Evaluation of the Developed Dryer

The developed dryer was tested for drying pineapples and carrots, reducing their initial moisture content from 90% and 88%, respectively, to 10% (wet basis). The amount of water evaporated from the 50 kg of drying products was calculated using Equation (6) and determined to be 44.4 kg for pineapples and 43.4 kg for carrots. The weight of the dried product removed from the dryer was 5.5 kg for pineapples and 6.6 kg for carrots. Figure 17 and 18 illustrate the drying curves for pineapples and carrots using solar energy with TES materials, without TES materials, and through OSD.

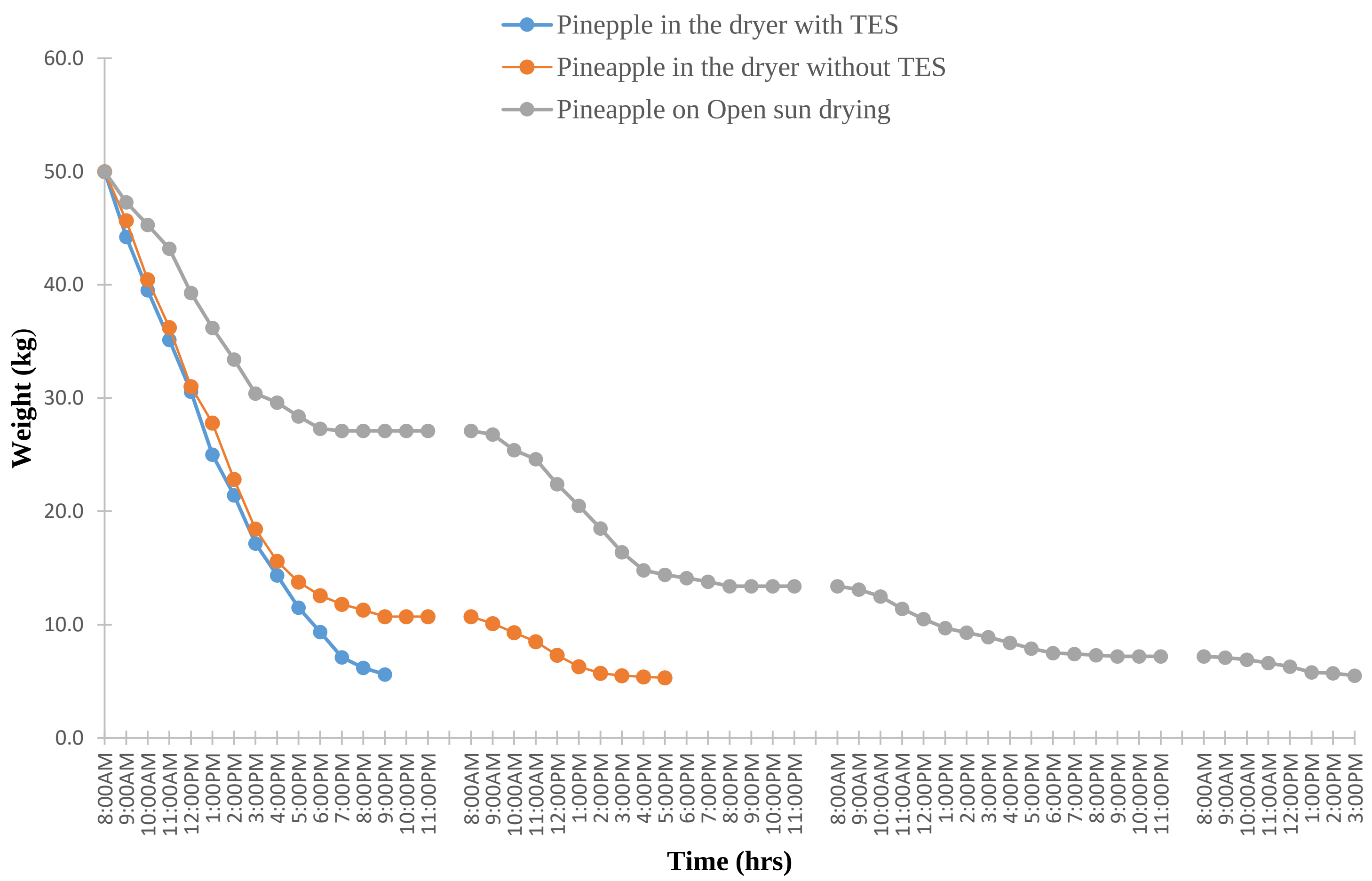

Figure 17: Weight reduction in the solar dryer with and without TES materials and OSD

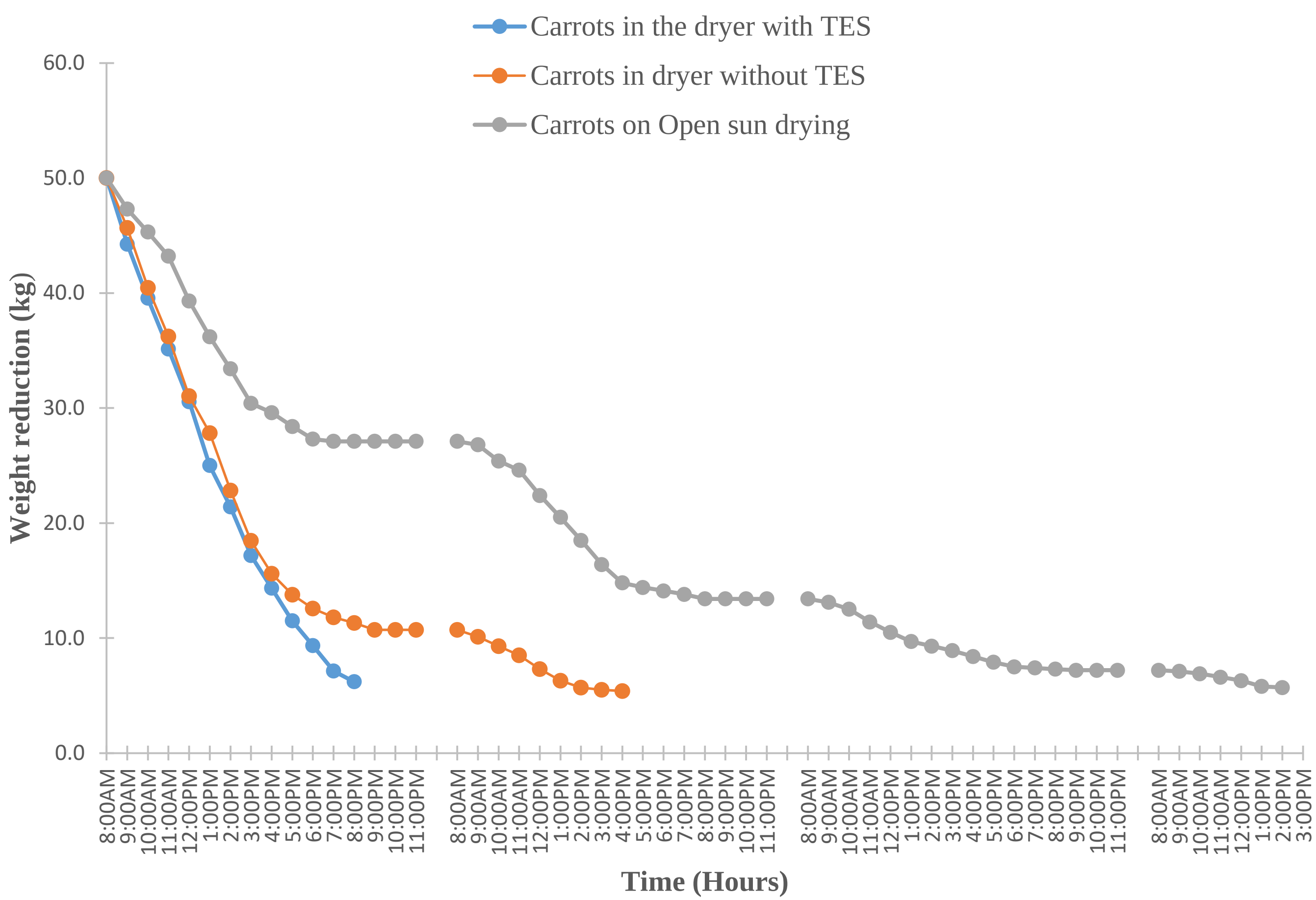

Figure 18: Weight change with time of carrots with and without TES materials and OSD

In all drying methods, the drying rate was initially rapid and gradually decreased over time. The drying times for pineapples were 13 hours with TES, 24 hours without TES, and 52 hours with OSD. For carrots, the drying times were 12 hours with TES, 23 hours without TES, and 50 hours with OSD. The use soapstone rocks helped maintain higher drying temperatures in the range of 62°C to 30°C within the drying chamber, along with lower relative humidity levels between 9% and 53%, thereby reducing the drying time. Compared to previous studies, these results align with the findings of Ahmad and Prakash (2020), who dried tomato flakes in a greenhouse dryer integrated with TES materials, reporting a reduction in moisture content from 96% to 9.10% (wet basis) in just 13 hours. The results also align well with the findings reported by Kareem *et al.* (2017), who investigated the performance of a multi-pass solar air heating system integrated with gravel as TES materials for drying Rosella. Their study noted a reduction in moisture content from 85.6% to 9.2% (wet basis) in 14 hours.

The drying rate was calculated using Equation (4) and found to be 3.4 kg/hr for pineapples and 3.3 kg/hr for carrots when using thermal energy storage. In contrast, the drying rates without energy storage were approximately 2.5 kg/hr, while OSD yielded a rate of only 0.6 kg/hr. In Furthermore, the dryer's thermal efficiency was estimated using Equation (5) and found to be 45%. The results are consistent with the findings of Mugi *et al.* (2022), who reported that the thermal efficiency of most solar dryers integrated with TES materials ranged from 9.9% to 58.2%.

The collector's efficiency with energy storage was calculated using Equation (6) and determined to be 43%. The obtained efficiency is consistent with the findings of Kesavan *et al.* (2019), who reported a collector efficiency of 45% for a triple-pass solar dryer integrated with sand as TES materials. However, the collector efficiency in this research is slightly different from the 22% reported Vijayan *et al.* (2016) for drying bitter gourd with pebble as TES and the 24% reported by Mohanraj and Chandrasekar (2008) for copra drying using sand as TES materials. These differences in efficiency may be attributed to the variation in the types of TES materials used.

The savings in drying time was calculated using Equation (8), were found to be 83%. This indicates that a solar dryer integrated with TES can reduce drying time by 83% compared to open sun drying (OSD). The results of this study are slightly better than those reported by Ayyappan *et al.* (2016) who noted time savings of 55% for coconut drying with concrete, 62% with sand, and 69% with rock as TES materials. The differences in savings are attributed to the varying drying times, which were 78 hours with concrete, 66 hours with sand, and 53 hours with rock, whereas OSD took 174 hours.

Table 14 compares the performance results of solar dryers equipped with various natural rocks like gravel, granite, pebbles, and sand, with respect to thermal efficiency, drying time, and collector efficiency. The findings show that the dryer with TES materials has the shortest drying time, followed by the dryer without TES materials, while OSD method takes the longest. For instance, Umayal-Sundari and Veeramanipriya (2022), evaluated the drying kinetics, morphological characteristics, and performance of untreated Carica papaya using a solar hybrid dryer that used gravel as a heat storage material. Their results revealed that the drying time for the solar dryer with TES materials was 5 hours, whereas it was 6 hours without TES materials, and 11 hours for OSD.

Additionally, the thermal drying efficiency and collector efficiency were higher for the solar dryers with TES materials compared to those without TES and OSD. In this study, pineapples required 13 hours to dry when TES materials were used, 24 hours without TES materials, and 52 hours using OSD. The thermal efficiency was recorded as 45% with TES materials, 38% without TES materials, and 25% for OSD. The collector efficiency was 43% with TES materials, compared to 36% without TES materials. These findings are consistent with the data in Table 14, which demonstrate that the thermal efficiency of solar dryers with TES materials is superior to those without TES materials and OSD. From the previous research work in Table 14, by Umayal-Sundari and Veeramanipriya (2022), the thermal efficiency of the solar dryer with TES materials was 34.5 %, without TES materials was 30.2 %, whereas with OSD was 19.3

Table 14: Performance comparisons with some previously published works

S/N	Types of Solar Dryer	Loading capacity of the product	Types of rock used	Drying time (h)			Dryer Thermal efficiency (%)			Collector efficiency (%)		References
				TES	NO TES	OSD	TES	NO TES	OSD	TES	NO TES	
1	Hybrid solar dryer integrated TES	2.5 kg of sliced Carica papaya per batch	Gravel	5	6	11	34.5	30.2	19.3			Umayal-Sundari and Veeramanipriya (2022)
2	Multi-pass solar air heating collector dryer	75.2-81.3 kg of Roselle	Granite	14		35	36.22	-		64.08		Kareem *et al.* (2017)
3	Solar dryer integrated with packed bed TES system	10 kg of sliced orange	Pebble	7	7.2	-	54.71-68.37	50.18-66.58	-			Atalay (2019)
4	Indirect solar dryer integrated with TES materials	0.8959 kg of tomato slices	Limestone	22	25		12.57	8.41				Cetina-Quiñones *et al.* (2021)
		0.9641 kg of sliced tomato	Beach sand	23	25		11.02	8.37				
5	Solar dryer integrated with STE and PCM	9 kg of chill	Gravel	21	96	150	15.62			78.02		Bhardwaj et al., 2020)
6	Triple –pass solar dryer	4 kg of potato	Sand	4.5		5	53.57			45		(Kesavan *et al.* (2019)
7	Indirect solar dyer integrated with TES materials	4kg of bitter gourd	Pebble	7		10	19			22		Vijayan *et al.* (2016)
8	Forced convection solar dryer	60 kg of copra	Sand	82		168				24		Mohanraj and Chandrasekar (2008)

S/N	**Types of Solar Dryer**	**Loading capacity of the product**	**Types of rock used**	**Drying time (h)**			**Dryer Thermal efficiency (%)**			**Collector efficiency (%)**		**References**
				TES	**NO TES**	**OSD**	**TES**	**NO TES**	**OSD**	**TES**	**NO TES**	
9	Greenhouse dryer	4 kg of tomato flakes	Gravel	13								Ahmad and Prakash (2020)
		5 kg of vitis vinifera	Sand	28	53	58	40					
10	Convectional solar dryer using TES materials											Natarajan *et al.* (2017)
		2 kg of momordica	Sand	5.3	7	10	42					
		Coconut	rock	53		174				11.65		
11	Greenhouse solar dryer integrated with TES materials	Coconut	Concrete	78		174				9.5		Ayyappan *et al.* (2016)
		Coconut	Sand	66		174				11		
12	Solar dryer integrated with TES materials	50 kg of pineapple and 50 kg carrot	Soapstone	13	24	52	45 38	25		43	36	Current study

4.3 Proximate of the Dried Products

One of the key factors in the drying process is preserving the nutritional value of the dried products. Figure 20 presents a comparative analysis of nutritional contents including carbohydrates, crude fiber, protein, fats, and ash between fresh and dried products using a dryer integrated with TES materials, without TES materials, and through OSD.

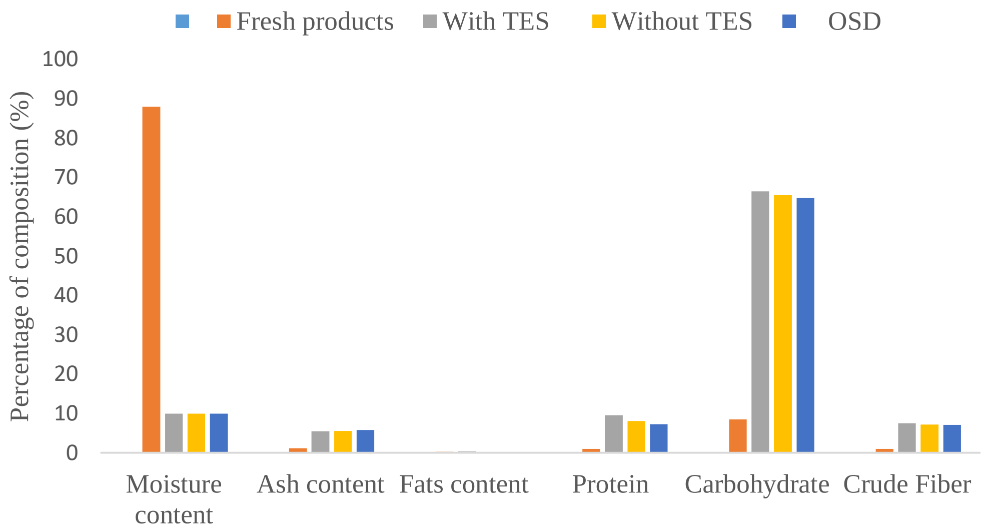

Figure 20: Graph of proximate analysis for pineapples

All drying methods successfully reduced moisture content to a desirable level of about 10%, which is safe for extending the shelf life of the products. The results indicate that all drying methods enhanced the concentrations of nutritional value in the dried products due to the removal of water from the fresh products. This implies that a similar quantity of the products contains more concentrated amounts of the same nutrients and calories compared to their fresh counterparts. According to Mongi and Ngoma (2022), the drying process decreases moisture content, which leads to an increase in soluble concentration.

Carbohydrates exhibited the highest concentration in the dried products, followed by protein, crude fiber, ash, while fat content was the least among all drying methods, as shown in Fig. 20. In terms of the drying methods, products dried using a dryer integrated with TES materials showed the highest nutrient concentrations, followed by those dried without TES materials, with the lowest concentrations observed in the products dried using OSD. For example, the carbohydrate composition for the dryer integrated with TES materials was 66.5%, while the compositions for the dryer without TES materials and open sun drying (OSD) were 65.4% and 64.8%, respectively. Similarly, the protein composition was 9.53% for the dryer with TES materials, compared to 8.1% for the dryer without TES and 7.3% for OSD. This is because the integration of TES materials allows for quicker evaporation of moisture at a uniform temperature (Bhardwaj *et al.*, 2020). These results are in agreement with previous studies by Seidu *et al.* (2012), who investigated the preservation of indigenous vegetables using solar drying technology. They found that solar dryer decreased moisture content and increased the concentrations of protein, fiber, ash, and fat compared to fresh products. Lakshmi *et al.* (2021), conducted an experimental investigation on an active solar dryer integrated with TES materials for drying black pepper. Their findings indicated that the drying process reduced moisture content and enhanced the concentrations of protein, fiber, ash, carbohydrates, and fat in the dried products compared to fresh ones. Similarly, Baloch *et al.* (2015), examined the proximate and mineral compositions of dried cauliflower using OSD and cabinet drying methods. It was found that drying reduced moisture content, and the concentrations of protein, fiber, ash, carbohydrates, and minerals in the dried products were higher compared to the fresh ones.

Proximate assessment was also performed on selected minerals, including calcium, sodium, phosphorus, and magnesium, as illustrated in Fig. 21 and 22 for carrots and pineapples, respectively. All drying methods resulted in increased mineral concentrations compared to the fresh products due to the removal of water from the fresh samples.

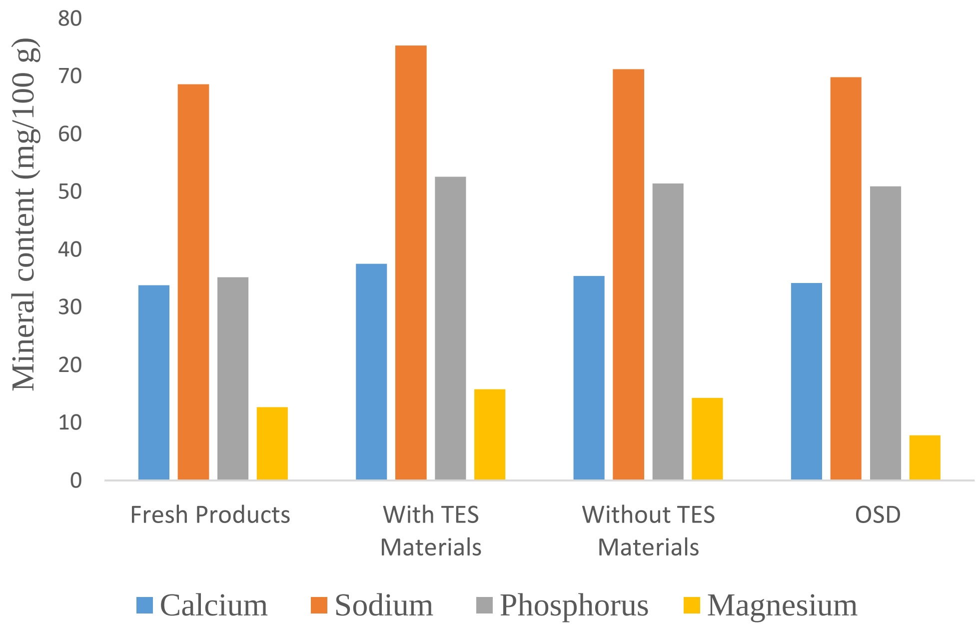

Figure 21: Graph of proximate analysis of minerals for carrots

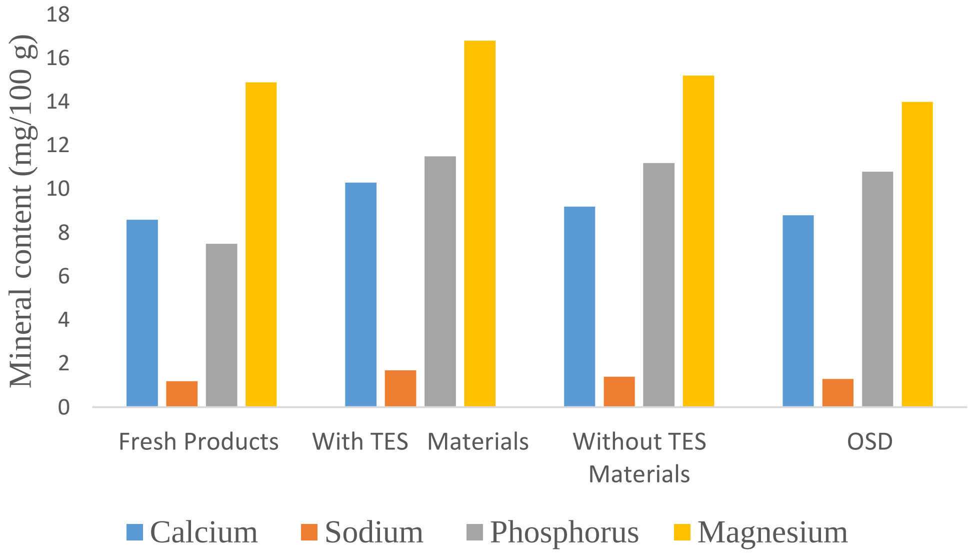

Figure 22: Graph of proximate analysis of minerals for pineapples

However, the mineral concentration was relatively higher in products dried using the solar dryer integrated with TES materials, followed by those dried without TES materials and those subjected to OSD. The results are consistent with those reported by Mohammed (2021), who conducted a proximate analysis of drying mangoes and pineapples using various solar drying technologies. It was reported that all solar drying methods increased the concentrations of mineral contents compared to the fresh products. The apparent increase in mineral content in dried products is primarily a result of the reduction in water content during the drying process, which concentrates the nutrients. While the absolute amount of minerals remains constant or changes minimally, their relative concentration per unit weight increases (Radojčin *et al.*, 2021). For example, if one compares 100 grams of fresh fruits or vegetables to 100 grams of dried products, the dried fruits will have higher concentration of nutrients because the water contents has been reduced. This doesn't mean that drying creates more mineral contents, but rather that the amount of mineral contents per unit weight is higher in the dried products due to removal of water.

The concentration of vitamin C was found to decrease across all drying methods; however, a significant increase in the concentration of vitamin A was observed compared to the fresh products, as shown in Table 15. For instance, the concentration of vitamin C in fresh carrots was 5.8 mg/100 g, while it was 5.6 mg/100 g with TES materials, 5.6 mg/100 g without TES materials, and 5.1 mg/100 g for open sun drying (OSD). The reduction in vitamin C concentration was slightly smaller when using a solar dryer integrated with TES materials compared to those without TES materials and OSD. This reduction in vitamin C is attributed to its thermal sensitivity. Vitamin C (ascorbic acid) is heat-sensitive and breaks down at elevated temperatures. In addition, Vitamin C is also sensitive to light, particularly ultraviolet rays, which can catalyze its degradation. The OSD, where products are exposed directly to sunlight, typically results in greater vitamin C losses compared to controlled drying methods (Giannakourou & Taoukis, 2021). The sensitivity arises from its chemical nature as a water-soluble, highly reactive compound as documented by Eze and Ojike (2012).

Table 15: Results of the proximate analysis for vitamins

Parameters	Fresh products (Control)		With TES materials		Without TES materials		OSD	
	Carrot	Pineapple	Carrot	Pineapple	Carrot	Pineapple	Carrot	Pineapple
Vitamin C (mg/100 g)	5.8	47.3	5.6	45.8	5.4	43.5	5.1	40.2
Vitamin A (mg/100 g)	880.5	55.7	897.2	68.1	891.8	58.2	885.6	56.5

Table 16 presents a comparison of the proximate results of solar dryers for various agricultural products from previous studies. The table indicates that all drying methods reduced moisture content and increased the concentrations of nutritional value in the dried products due to the removal of water from the fresh products. In most previous studies, an increase in the concentrations of carbohydrates, fats, fiber, and ash was reported, with only minor losses in vitamins and fats when using different types of solar dryers. However, significant losses in nutritional composition were noted when using OSD. The results presented in Table 16 align with those obtained from this experiment. For instance, Mongi and Ngoma (2022), studied the effects of solar drying methods on the proximate composition, sugar profile, and organic acids of various mango varieties in Tanzania. They conducted a proximate analysis for moisture content, protein, fats, crude fiber, ash, carbohydrates, and minerals using two types of dryers: The cabinet mixed-mode dryer and the tunnel dryer. The findings revealed that both drying methods reduced moisture, protein, fats, crude fiber, and minerals compared to fresh products, with greater losses observed when using the tunnel dryer method. However, carbohydrates were found to be higher in the dried products compared to the fresh ones. Baloch *et al.* (2015), carried out a proximate and mineral composition analysis of dried cauliflower using the cabinet dehydration method. The proximate analysis examined moisture content, fat, ash, protein, fiber, carbohydrates, and minerals. The results indicated that drying reduced moisture content while increasing the levels of protein, fiber, ash, carbohydrates, and minerals. In addition, Lakshmi *et al.* (2021), did an experimental investigations on active solar dryers integrated with thermal storage for drying black pepper using a solar dryer equipped with TES materials. The proximate analysis assessed moisture content, protein, fats, fiber, ash, carbohydrates, and texture. The results indicated that drying reduced moisture content while increasing the levels of protein, fiber, ash, fats, carbohydrates, and texture in the dried product compared to the fresh product.

Table 16: Comparison of the proximate analysis with some previous works

S/N	Types of Solar Dryer	Product analyzed	Drying temperature (°C)	Parameters analyzed	Findings	Reference
1	Cabinet mixed-mode dryer (CMG) and Tunnel dryer (TD)	Mango	30-55 in CMG and 30-73 in TD	Moisture, Protein, Fats, crude fiber, Ashes, carbohydrate and Minerals (Ca, Fe, K, Mg, Na, P)	Both drying methods reduced moisture, protein, fats, crude fiber, and minerals compared to fresh products, with greater losses observed using the tunnel drying (TD) method. However, the levels of carbohydrates were higher in the dried products compared to the fresh ones.	Mongi and Ngoma (2022)
2	OSD	Raspberries and Blueberries	40-60	Moisture, Fat, Ashes, Protein, Antioxidant activity, Total phenols and Total sugar	Drying resulted in a reduction of moisture, fat, ash, antioxidant activity, and total phenolic content, while protein and total sugar levels increased in the dried products compared to the fresh ones	Catorze *et al.* (2022)
3	OSD, Shade drying and Oven drying	Moringa Oleifera leaves	25 for shade and 60 for oven drying	Moisture, Fat, Ashes, Protein, fiber, Ashes, carbohydrate, vitamins and Minerals (Zn, Ca, and Fe)	The three drying methods reduced moisture, fats and iron whereas protein, ash, fibers, carbohydrate, vitamin, Zinc and calcium were increased as compared to fresh products.	Mbah *et al.* (2012)
4	Cabinet dehydration	Cauliflower	70	Moisture, Fat, Ashes, Protein, fiber, Ashes, Carbohydrate, and Minerals (K, Ca, Mg, Fe, P, Zn)	Drying reduced moisture contents, however increased protein, fiber, ashes, carbohydrate and minerals.	Baloch *et al.* (2015)

S/N	Types of Solar Dryer	Product analyzed	Drying temperature (ºC)	Parameters analyzed	Findings	Reference
5	Direct solar dryer	Cocoyam leaves	26.23-47.32	Moisture, Protein, Fat, Fiber, Ash and Carbohydrate	Drying resulted in a reduction of moisture and fat, while simultaneously increasing the levels of carbohydrates, protein, fiber, and ash compared to fresh products.	Seidu *et al.* (2012)
6	Air oven	Tomato	70-90	Moisture, Protein, Fat, Fibre, Ash, Carbohydrate and vitamin C	Drying led to a reduction in moisture, protein, fats, fiber, and vitamin C, while increasing the levels of ash and carbohydrates.	Yusufe *et al.* (2017)
7	Solar dryer integrated with TES	Black pepper	47.1	Moisture, Protein, Fats, fiber, Ashes, Carbohydrate and Texture	Drying decreased moisture content while increasing the levels of protein, fiber, ash, fat, carbohydrates, and texture in the dried product compared to the fresh one. However, antioxidant activity and total phenolic content were higher in fresh black pepper.	Lakshmi *et al.* (2021)
8	Solar dryer integrated with TES	Pineapple and Carrot	40-62	Moisture, Protein, Fats, crude fiber, Ashes, Vitamin (A and C), Carbohydrate and Minerals (Ca, Mg, Na, P)	Drying reduced moisture while increasing the concentrations of carbohydrates, fiber, ash, minerals, and protein, with only a minor loss of fats.	Current study

4.4 Techno-Economic Analysis

To calculate the annualized cost and other economic parameters, the initial capital cost must first be determined as a fundamental step in the economic analysis process. The initial capital cost for the materials was determined and found to be $ 5430.9 as shown in Table 17. Table 18 shows the some parameters used for estimations of operation costs.

Table 17: Details of materials costs for the development of the solar dryer (Capital cost)

S/N	Item Description	Unit	Quantity	Unit cost ($)	Amount ($)
1.	Mild steel sheet (2440 x1220 x1.5 mm)	pcs	23	74.8	1720.0
2.	Aluminum plate (2440 x1220 x 1.5 mm)	pcs	20	104.3	2087.0
3.	Mild steel hollow section (6000 x 40 x 3 mm)	pcs	10	52.2	521.7
4.	Solar collector glasses (2000 x1000 x 6 mm)	pcs	3	76.1	228.3
5.	Wind air ventilator	pcs	1	239.1	239.1
6.	Insulation materials (Fiber wool)	Roller	4	87.0	347.8
7.	Bolts and nuts (M12 x 50 mm)	kg	2	8.7	17.4
8.	Black paint	litres	5	2.6	13.0
9.	Red oxide primer	litres	10	2.6	26.1
10.	Silver paint	litres	5	6.5	32.6
11.	Thinner (High gross)	litres	5	2.6	13.0
12.	Filler	kg	5	6.5	32.6
13.	Welding rod	kg	25	2.6	65.2
14.	Cutting disc	pcs	10	4.3	43.5
15.	Grinding disc	pcs	10	4.3	43.5
	Sub-total				**5430.9**
16.	Labor charges for fabrication and installation				210
	Total				**5640.9**

Table 18: Operation cost (OPEX)

S/N	Indicator	Value ($)
1.	Annual cost of the fresh pineapples	3125
2.	Annual cost of the fresh Carrots	2500
3.	Annual labor charge	250
4.	Maintenance cost	50
	Total	**5925**

4.4.1 Annualized Cost Method

According to Bishoge *et al.* (2018), Tanzania experiences global horizontal solar radiation ranging from 4 to 7 kWh/m²/day and enjoys 2800 to 3500 sunshine hours annually. Since the solar dryer operates exclusively on solar energy, it is estimated to function for approximately 200 days each year. During testing, 50 kg of fresh pineapples and 50 kg of fresh carrots were dried until their moisture content was reduced to around 10%. The final weights of the dried products were recorded as 5.5 kg for pineapples and 6.6 kg for carrots. The annualized cost of operating the dryer, calculated using equation 16, amounted to $562.70. Using Equation 21, the estimated annual output was 1100 kg of dried pineapples and 1320 kg of dried carrots. Additionally, the cost of drying one kilogram of pineapple and carrot, determined using Equation 22, was $0.51 and $0.43, respectively.

4.4.2 The life Cycle Savings

The lifecycle savings method involves calculating daily savings and projecting the present value of annual savings over the dryer's operational lifespan. Based on Equation 23, for pineapples and carrots, the projected cost of fresh items per kilogram of dry product was $2.78/kg and $1.94/kg, respectively. Using equation 24, the total drying cost per kilogram was determined to be $2.78/kg for pineapples and $1.90/kg for carrots. Daily batch-wise savings, calculated using equation 26, were $19.20 for pineapples and $17.90 for carrots.

The annual savings, present value savings, and cumulative present worth savings throughout a 20-year dryer lifespan are summarized in Table 19. The annual savings are projected to be $9814.50 for pineapples and $9121.20 for carrots, while the cumulative present worth savings are $62232.70 for pineapples and $57 836.30 for carrots. With an initial investment of $5430.90 for the dryer, the total savings over 20 years would be $62 232.70 for pineapples and $57 836.30 for carrots. According to Cui *et al.* (2022), higher present cumulative value indicate better project.

Table 20 lists a few previous research that examined the economics of several types of solar dryers. This results is in agreements with the results reported Philip *et al.* (2022), who used greenhouse solar dryer to dry tomato, carrot and bitter gourd. It was reported that annualized cost was found $ 397.19. However, the Cumulative present worth was found $ 27 579 for tomato, $ 22 039 for carrot and $ 19 316 for bitter gourd which is smaller as compared to this particular study.

Table 19: Annual saving, NPW and CPW for drying pineapple and carrots

Year	Pineapple			Carrot		
	Annual Savings ($)	Net present worth ($)	Cumulative present worth ($)	Annual Savings ($)	Net present worth ($)	Cumulative present worth ($)
1.	4026.62	3763.20	3763.20	3742.14	3497.33	3497.33
2.	4219.95	3685.87	7449.06	3921.81	3425.46	6922.79
3.	4422.55	3610.12	11059.18	4110.11	3355.07	10277.86
4.	4634.88	3535.93	14595.11	4307.44	3286.13	13563.99
5.	4857.41	3463.26	18058.38	4514.25	3218.59	16782.58
6.	5090.61	3392.09	21450.46	4730.98	3152.45	19935.03
7.	5335.01	3322.37	24772.84	4958.11	3087.66	23022.70
8.	5591.13	3254.09	28026.93	5196.15	3024.21	26046.90
9.	5859.56	3187.21	31214.14	5445.61	2962.05	29008.96
10.	6140.86	3121.70	34335.84	5707.05	2901.18	31910.13
11.	6435.67	3057.54	37393.38	5981.04	2841.55	34751.68
12.	6744.63	2994.70	40388.08	6268.17	2783.14	37534.82
13.	7068.42	2933.14	43321.23	6569.09	2725.94	40260.76
14.	7407.76	2872.86	46194.08	6884.46	2669.91	42930.68
15.	7763.38	2813.80	49007.89	7214.96	2615.03	45545.71
16.	8136.066	2755.967	51763.85	7561.328	2561.283	48106.99
17.	8526.646	2699.318	54463.17	7924.319	2508.637	50615.63
18.	8935.973	2643.832	57107	8304.735	2457.071	53072.7
19.	9364.947	2589.486	59696.49	8703.41	2406.565	55479.27
20.	9814.513	2536.257	62232.75	9121.222	2357.097	57836.36

4.4.3 Payback Period

The payback period was calculated using Equation (31), and found to be to be 1.5 years for pineapples and 1.6 years for carrots. This indicates that it will take 1.5 years to recover the initial investment of $5430.90 for drying pineapples and 1.6 years for carrots. The payback period of 1.5 years for pineapples and 1.6 years for carrots is significantly shorter than the 20-year lifespan of the solar dryer, highlighting its economic viability.

Table 20 presents a comparison of various previous studies on the economic analysis of different solar drying technologies. The findings align with the results presented by Philip *et al.* (2022), who used greenhouse solar dryer to dry tomato, carrot and bitter gourd. It was reported that annualized cost was found $ 397.19. However, the Cumulative present worth was found $ 27 579 for tomato $ 22 039 for carrot and $ 19 316 for bitter gourd which is smaller as compared to this particular study. Poonia *et al.* (2019), conducted an economic analysis of an inclined solar dryer for the drying of fruit and vegetables using an inclined solar dryer.

The economic analysis's findings indicated that the annualized cost was $132.80.The life-cycle savings were found to be $ 514.4 and the payback period was 1.42 years. This results is in line with Sreekumar (2010), who examined the techno-economics of a solar air heating system incorporated into a roof for the purpose of drying fruits and vegetables. The methods used were life-cycle savings, annualized cost, and payback period. The results of the economic analysis were: the annual capital cost was found to be $1244.2, the life cycle savings were found to be $20 954; and the payback period was 0.54 years.

Table 20: Some of the previously works on economic analysis of different solar drying technologies

S/N	Type of Solar dyer	Type of dried product	Weight of the product (kg)	Initial investment cost ($)	Life span	Method used	Findings	Reference
1.	Greenhouse solar dryer	Tomatoes, carrots and bitter gourds	100	2631	20	Annualized cost, Life cycle savings and payback period	The annualized cost was found $ 397.19. Cumulative present worth was found $ 27 579 for tomato, $ 22 039for carrot and $ 19 316 for bitter gourd. Payback period was 1.49 years for tomato, 1.87 for carrot and 2.14 for bitter gourd.	Philip *et al.* (2022)
2.	Indirect solar dryer with PCM materials	Leafy herbs	12	1210.72	12	Net present value (NPV), profit and payback period	NPV was found $ 4.836. Profit $ 798 and payback period 1.5 years.	Jain and Tewari, (2015)
3.	Solar dryer integrated with PCM materials	Blood fruits	20	507.4	20	Net economic benefit, benefit to cost ratio and payback period	Net economic benefit was found $ 263.3, benefit to cost ratio 2.07 and payback period 2.16 years.	Kondareddy *et al.* (2021)
4.	Roof-integrated solar air heating system	Pineapples	200	6766.7	20	Annualized cost, Life cycle savings and payback period	The annual capital cost was found $ 1244.2. The life cycle savings was found $ 20, 9154 and payback period 0.54 years.	Sreekumar (2010)

S/N	Type of Solar dyer	Type of dried product	Weight of the product (kg)	Initial investment cost ($)	Life span	Method used	Findings	Reference
5.	Inclined solar dryer	Tomatoes	120	110.7	10	Annualized cost, Life cycle savings and payback period	Annualized cost was found to be $ 132.8. The life cycle savings was found $ 514.4 and payback period 1.42 years.	Poonia *et al.* (2019)
6.	Cabinet dryer	Bottle gourds	100	22 560	20	Annualized cost, Life cycle savings, payback period and internal rate of return.	The cost for drying 1 kg of died bottle gourds was found to be $ 0.68. The present cumulative worth was found $ 23 027. Payback period was found to be 1.909 years and internal rate of return 6.	Chavan and Thorat (2021)
7.	Solar dryer integrated with TES materials	Pineapples and Carrots	50	5430.9	20	Annualized cost, Life cycle savings, payback period	The annualized cost was found to be $ 562.7. The cumulative present worth was found to be $ 62 232.7 and $ 57 836.3 for pineapple and carrots, respectively. The payback period for pineapple is 1.5 years whereas for carrots it is 1.6 years.	Current study

4.5 The life cycle Assessment

Figure 23 shows the results of Life Cycle Impact assessment of the solar dryer integrate with TES materials for midpoint category. The midpoint characterization impacts were evaluated for 18 categories. It can be clearly seen that mild steel showed higher percentage of midpoint category in technology fabrications compared to aluminum materials, This is due to the facts that most of the materials processing such as welding, cutting and joining were done with steel sheet. The dryer also used more steel materials about 806 kg compared to aluminum 240 kg. The human carcinogen toxicity category recorded highest 63.6 % of mild steel and the lowest 60.9% was recorded with ionizing radiation category. Aluminium materials processing recorded lowest 33.2% for ionizing radiation category and highest was 34.7% for human carcinogen toxicity category.

Figure 23: **Percentage of materials contributions for midpoint category of solar dryer fabrication processes**

Percentage of materials contribution of Life cycle assessment impact assessment for endpoint three category; human, ecosystem and resources is presented in Fig. 24. It can be seen that mild steel contributed a higher damage percentage than aluminum during the material fabrication process because most of the fabrication work, such as welding, was done for steel.

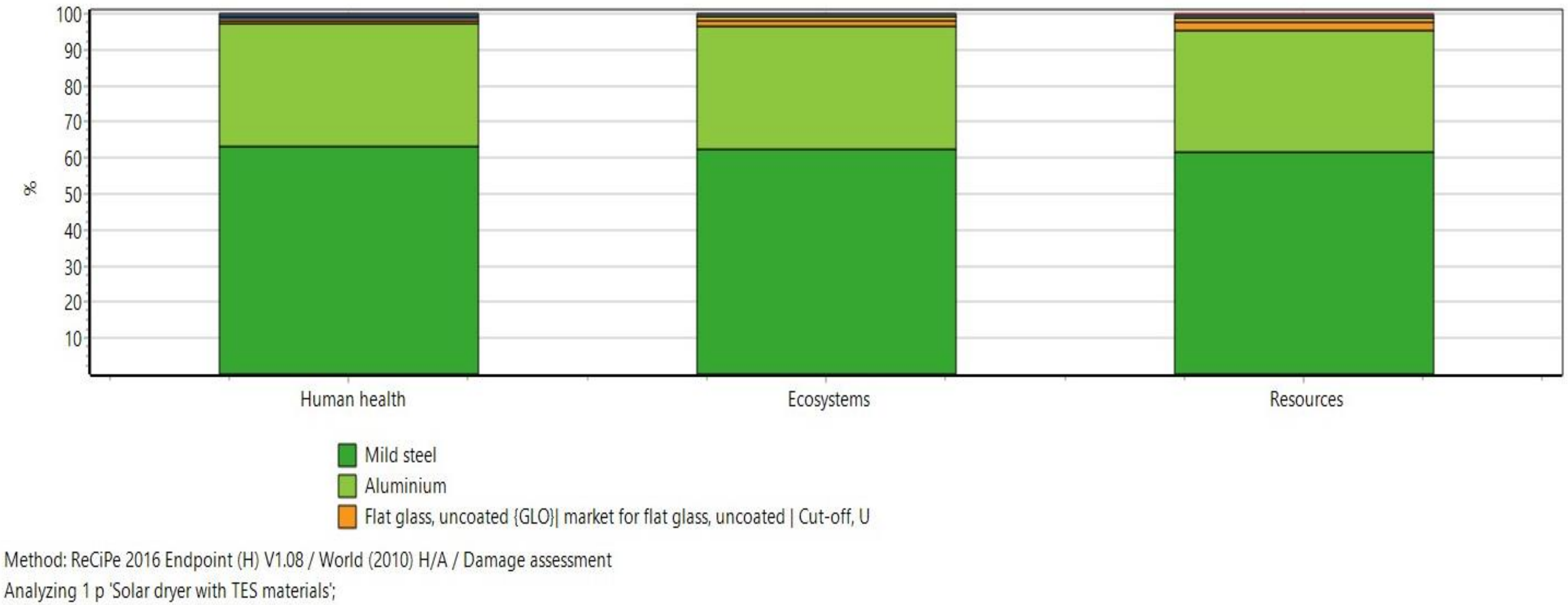

Figure 24: Midpoint category assessment of the solar dryer during fabrication processes

Figure 25 shows the life cycle impact assessment for a single score of the materials and process of the solar dryer. It can be seen that the human health category showed higher environmental impact inters of material extraction, followed by ecosystems and resources. Steel materials had a higher environmental impact of about 260 pt in the category of human health, whereas aluminum showed 142 pt under the same category.

Steel welding and drilling contributed to 0.563 pt and 3.43 pt, respectively, under the human health category. Aluminum processing by drilling recorded 3.44 pt environmental impact. For ecosystem steel and aluminum recovered 254 pt and 138, respectively. The obtained results are inconsistency with the results reported by Nayanita *et al.* (2022) , who conducted LCA of mixed-mode type and direct mode type solar dryers using Simapro 8.3.0.0. It was reported that the endpoints using single score impact assessment for mixed-mode type were 16.5 pt, 1.22 pt, and 25.99 pt for human health, ecosystems, and resources, respectively, whereas for direct mode type they were 7.14 pt, 0.599 pt, and 15.48 pt for human health, ecosystems, and resources, respectively.

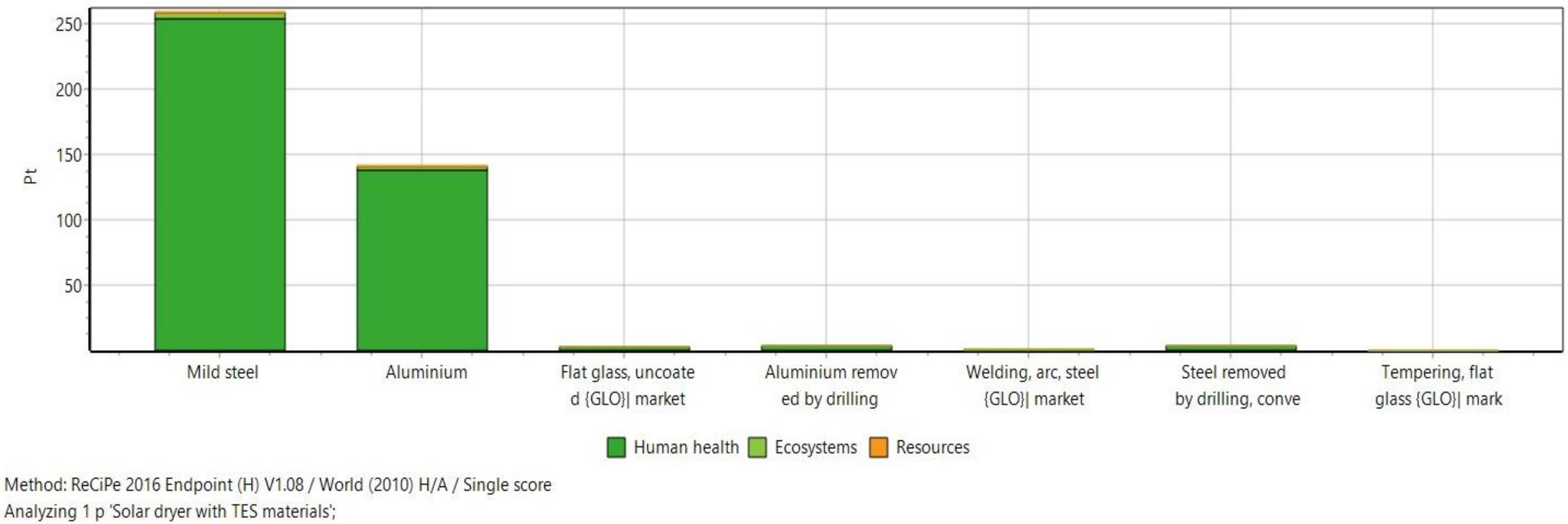

Figure 25: Life cycle assessment for a single score of the materials process for a solar dryer

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, a solar dryer incorporating soapstone as a thermal energy storage (TES) material was designed, constructed, and evaluated for its technical performance, proximate analysis, techno-economic analysis, and life cycle assessment. Drying experiments were conducted on pineapples (*Ananas comosus*) and carrots *(Daucus carota*) using two modes: With and without TES materials and the results were also compared OSD. The average initial moisture content of the pineapples and carrots decreased from 90% and 88%, respectively, to 10% wet basis (wb) over a duration of 12 hours. To evaluate the economic and environmental implications of the developed solar dryer, techno-economic and life cycle assessments were performed. The economic analysis included an assessment of annualized costs, lifecycle savings, and the payback period. For the life cycle assessment, Simapro 9.5.0.0 was utilized, incorporating the ReCiPe 2016 midpoint and endpoint global methods. The assessments focused on material extraction and fabrication.

Based on the study, the following conclusion can be drawn:

(i) The dryer integrated with TES materials was able to provide heat to the drying chamber for an additional 3–4 hours after sunset, due to the heat stored in the soapstone rocks.

(ii) The drying times for pineapples were 13 hours with TES materials, 24 hours without TES materials, and 52 hours for open sun drying (OSD). For carrots, the drying times were 12 hours with TES, 23 hours without TES, and 50 hours for OSD. This indicates that the dryer integrated with TES materials significantly reduces drying time compared to OSD and also when used without TES materials

(iii) Savings in drying time were found to be 75%. This indicates that the developed solar dryer integrated with TES materials can save 75% of the drying time compared to OSD.

(iv) The thermal energy stored in the soapstone rocks materials during the charging process was determined and found to be 8.8 MJ, whereas the amount of energy discharged from the rocks was found to be 6.5 MJ, resulting in a storage efficiency of 74.5 %.

(v) The thermal efficiency of the dryer using TES materials was found 45%, while it was 38% without TES materials and 25% for OSD. Additionally, the collector efficiency was 43% when TES materials were utilized and 36% without them.

(vi) The proximate analysis indicated that all drying methods led to an increase in the concentrations of carbohydrates, protein, crude fiber, ash, minerals, and vitamin A, with the highest concentrations observed when using a solar dryer integrated with TES materials.

(vii) The techno-economic analysis revealed that the initial investment for the solar dryer was $5430.9. The cumulative present value was calculated to be $62 232.70 for pineapple and $57 836.30 for carrots. The payback period was determined to be 1.6 years for pineapple and 1.7 years for carrots, indicating a relatively short return on investment compared to the dryer's lifespan of 20 years.

(viii) The life cycle assessment indicated that steel materials had a greater environmental impact during material extraction and fabrication compared to aluminum materials in both midpoint and endpoint categories. The damage assessment further revealed that the environmental impact was most pronounced on human health, followed by ecosystems and resource depletion.

(ix) Based on the life cycle assessment, the fabrication process contributed to relatively minor environmental impacts when compared to the material extraction phase.

(x) Based on the performance evaluation, techno-economic analysis, and life cycle assessment, the solar dryer integrated with soapstone as a thermal energy storage material presents a suitable technology for drying agricultural products. This approach can effectively reduce post-harvest losses and enhance food security, particularly in rural communities.

5.2 Recommendations

Based on the findings of this study, the following recommendations are made:

(i) Additional research is required to investigate the performance and limitations of soapstone in agricultural drying applications across various weather conditions and seasons.

(ii) Future research should prioritize the optimization of solar drying techniques, the exploration of innovative designs and materials, and the integration of advanced control systems to improve the performance and adaptability of solar dryers.

(iii) It is essential to conduct techno-economic and life-cycle assessment studies for all newly developed and emerging technologies to ensure economic viability and environmental sustainability.

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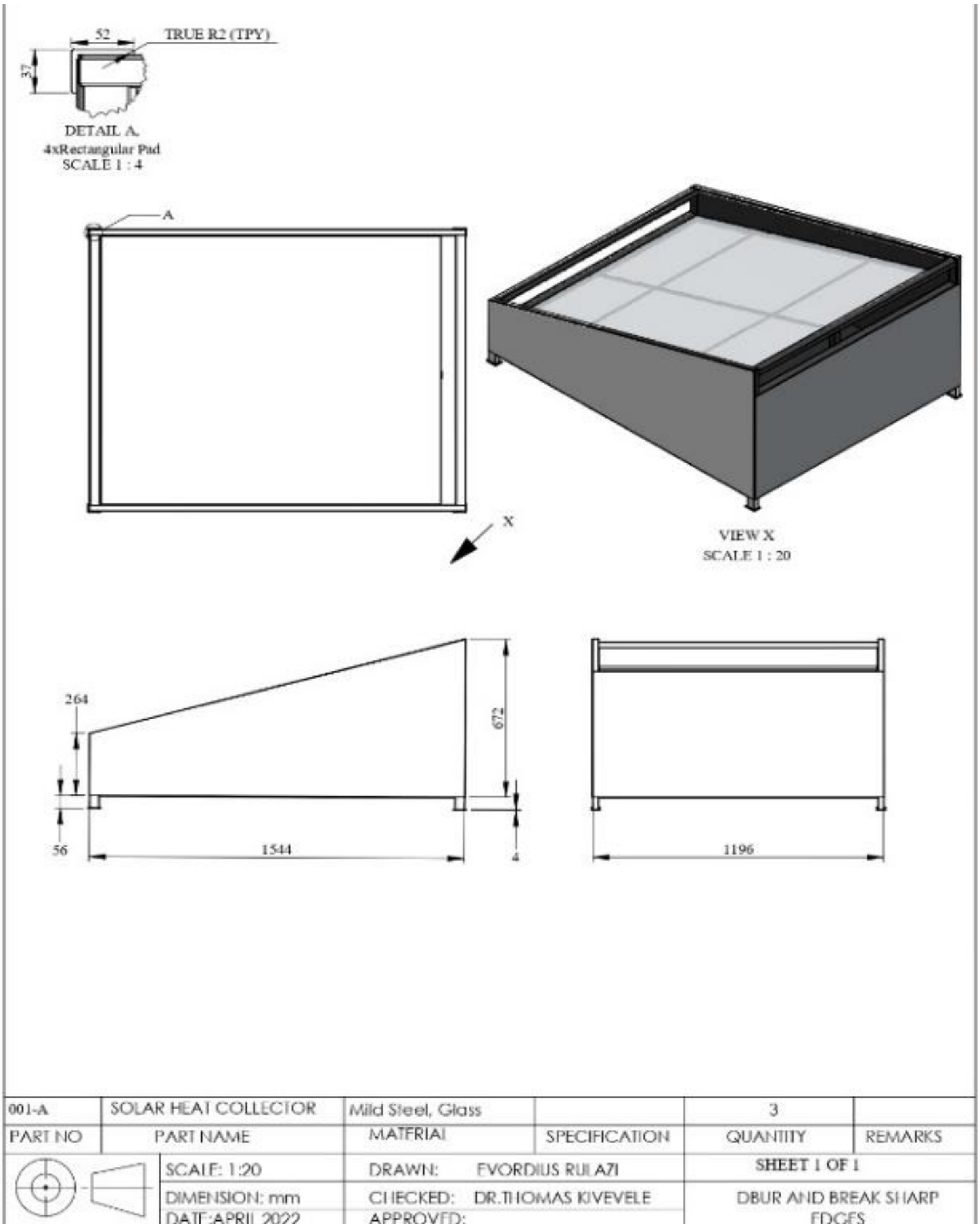
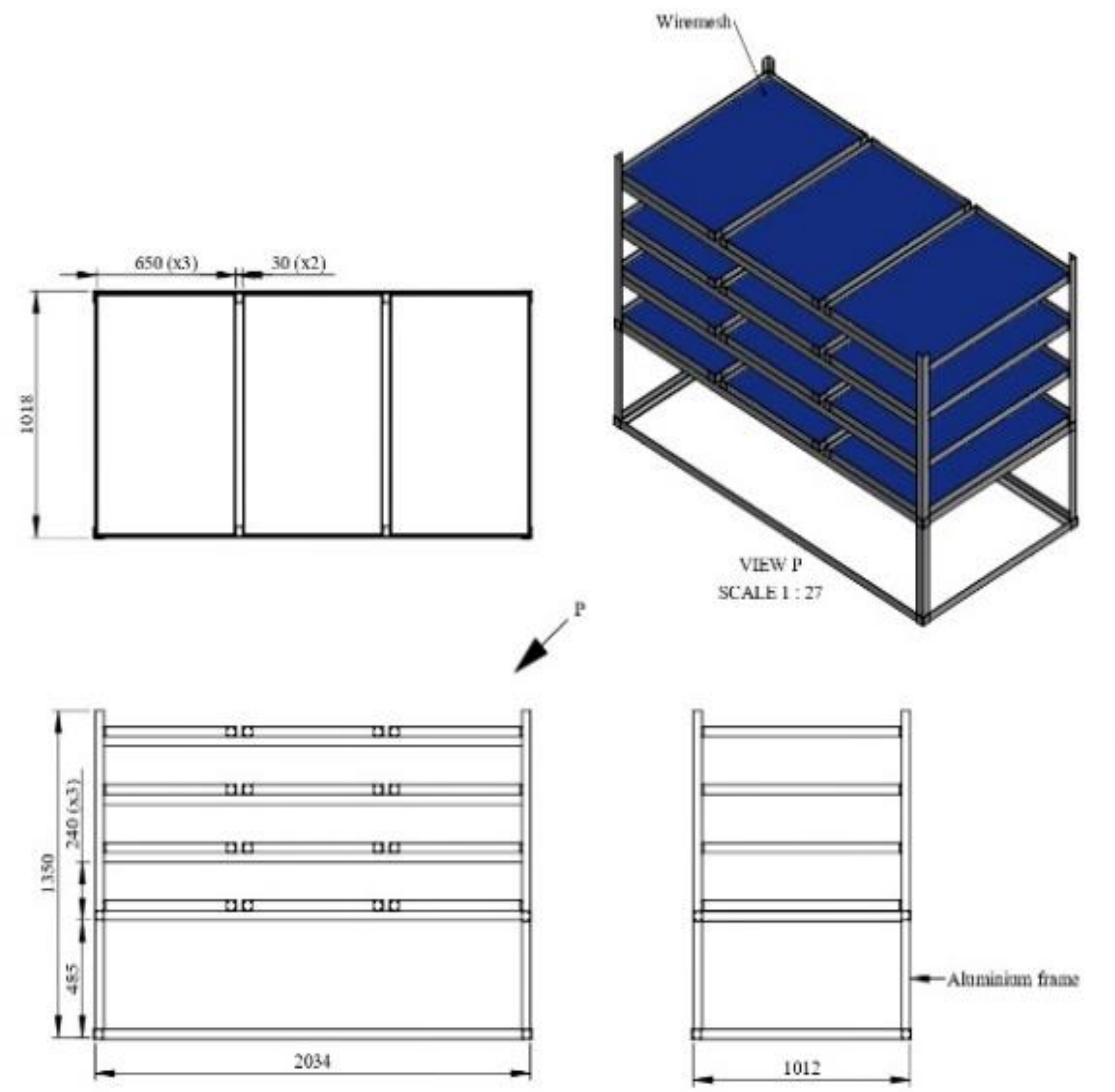
APPENDICES

Appendix 1: Schematic drawing of the solar collector



Appendix 2: Schematic drawing of the trays



001-A	Frame Sub-Assembly	Ms-Angle iron	30x30x1.5x2008	01	
PART NO	PART NAME	MATERIAL	SPECIFICATION	QUANTITY	REMARKS
	SCALE: 1:20	DRAWN: EVORDIUS RULAZI		SHEET 1 OF 1	
	DIMENSION: mm	CHECKED: DR.THOMAS KIVEVELE		DBUR AND BREAK SHARP EDGES	
	DATE:APRIL 2022	APPROVED:			
NM-AIST P.O.BOX 447 ARUSHA		Development and evaluation of solar dryer integrated with thermal energy storage system for drying of agricultural products		DRG No. 001	FORMAT A4

Appendix 3: Fabrication process to solar dryer application

Fabrication of a solar dryer

Painting of tarmac/tar in the solar collector

Integration of soapstone rocks

Mwambesi women group in Arusha receiving onsite training on solar drying technology as a part of farmer's engagement in PHLs management

The Mwambesi women group in Arusha visits the Upendo women group in Moshi to share their experiences with solar drying.

Hon. Prof. Joyce Ndalichako receiving information on solar dried products during sabasaba exhibitions in 2022.

Dr Janeth Marwa and Evordius Rulazi showcasing solar drying technology during TCU exhibitions in 2022.

RESEARCH OUTPUTS

(i) Publications

Rulazi, E. L., Marwa, J., Kichonge, B., & Kivevele, T. (2023). Development and Performance Evaluation of a Novel Solar Dryer Integrated with Thermal Energy Storage System for Drying of Agricultural Products. *ACS omega*, *8*(45), 43304-43317.

Rulazi, E. L., Marwa, J., Kichonge, B., & Kivevele, T. T. (2024). Techno-economic analysis of a solar-assisted heat pump dryer for drying agricultural products. *Food Science & Nutrition*, 12(2), 952-970.

(ii) Patent

A patent on solar dryer integrated with thermal energy storage system for drying of agricultural products from Business Registration and Licensing Agency (BRELA)

(iii) Poster presentation

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Development and Performance Evaluation of a Novel Solar Dryer Integrated with Thermal Energy Storage System for Drying of Agricultural Products

Evordius Laurent Rulazi, Janeth Marwa, Baraka Kichonge, and Thomas Kivevele*

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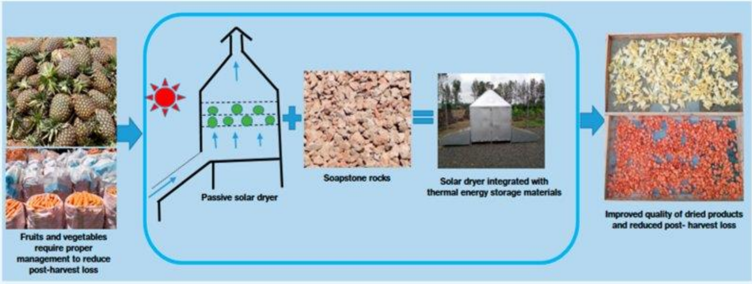

ABSTRACT: Passive solar dryers play a crucial role in reducing postharvest losses in fruits and vegetables, especially in regions like sub-Saharan Africa with low electrification rates and limited financial resources. However, the intermittent nature of solar energy presents a significant challenge for these dryers. Passive solar dryers integrated with thermal energy storage (TES) can reduce intermittence and improve the drying efficiency. Currently, phase change materials (PCMs) are popular heat storage materials in dryers, and paraffin wax dominates. The main problem with the use of PCMs is that it is necessary to closely constrain the temperature range of the process during charging and discharging. This can be a difficult condition to meet in simple solar dryers due to the variable availability of solar radiation. Instead, solid-phase materials, such as sand and rocks, are often used. Soapstone is one of the natural rocks with good thermal properties, but it has yet to be used as a TES material in solar dryers for drying agricultural products. Therefore, the main objective of the present study was to develop a novel solar dryer integrated with soapstone as a TES material and evaluate its performance. The proximate analysis to examine the quality of dried products using the developed technology was also carried out. The comparative experiments for the developed dryer were conducted in two modes: dryer with TES materials and without TES materials, and the results were compared with open sun drying (OSD) by drying 50 kg of fresh pineapple and carrot at different times. The drying times for pineapples in the dryer with TES, without TES, and OSD were 13, 24, and 52 h, respectively. However, the drying times for carrots in the dryer with TES, without TES, and OSD were 12, 23, and 50 h, respectively. Notably, the dryer integrated with TES materials could supply heat for around 3−4 h after sunset. The thermal efficiency of the dryer, collector efficiency, and storage efficiency of TES materials were calculated and found to be 45, 43, and 74.5%, respectively. Proximate analysis indicated that the dryer integrated with TES materials effectively maintained the quality of the dried products compared to OSD. Solar dryer integrated with soapstone showed great promise as sustainable and efficient solutions for reducing postharvest losses and enhancing food security in resource-constrained regions like sub-Saharan Africa.

1. INTRODUCTION

Fruits and vegetables contain essential components for human health such as proteins, vitamins, carbohydrates, fats, and minerals.[1] However, fruits and vegetables are perishable products and hence susceptible to postharvest losses. Lipinski, Hanson, Waite, Searchinger, and Lomax[2] published a working paper on reducing food waste and reported that global postharvest losses in cereal crops were about 19%, root crops about 20%, and fruits and vegetables 44%. According to the Ministry of Agriculture,[3] postharvest losses in Tanzania ranges 30−40% for cereal crops and higher for perishable crops such

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as vegetables and fruits, which lead to food insecurity and hunger.

The most common method used by farmers in reducing postharvest losses, especially in developing countries, is open sun drying (OSD). OSD is one of the oldest, cheapest, simple, and most widely used traditional methods in which products are spread on the ground and often rotated until sufficiently dried.[4] Despite its low cost and simplicity, OSD has some limitations, such as long drying time, contamination by insects, and loss of quality of dried products,[5] loss of color,[6] and the complexity of controlling drying parameters such as temperature, air velocity, and humidity.[7] Small-scale solar energy technologies such as solar dryers are being developed to address the challenges exhibited by OSD.[8] Solar dryers are specialized devices that control the drying process and protect agricultural produce from damage by insects, dust, and moisture. In comparison to drying products in the open sun, solar dryers generate higher temperatures and lower relative humidity and increase air flow across the produce, resulting in shorter drying periods, lower product moisture content, and reduced spoilage during the drying process. Solar dryers are more attractive because they can dry the product rapidly, uniformly, and hygienically to meet the required standards with zero energy costs.[9]

Depending on the mechanism of air flow, solar dryers can be divided into active and passive.[10] Active solar dyers are generally incorporated with active components such as a fan or heat pump to move the heated air from the collector to the drying chamber, hence suitable for large-scale drying operations.[11] Active solar dryers require substantial capital investments and burn significant amounts of fossil fuel,[12] making them unsuitable for rural areas, particularly in sub-Saharan Africa, where the electrification rate is low and financial resources are limited.[13] Passive solar dryers use only solar energy and do not use any active components, making them ideal for small-scale holders and agro-processors with limited resources, such as those in rural sub-Saharan Africa, due to attributes such as low capital investment and maintenance costs.[11,13] The most significant drawback of passive solar dyers is their intermittent nature, as they rely totally on the availability of sun radiation.[14] Passive solar dryers are thus ineffective during cloudy days or nighttime, demanding alternative solutions to these limitations. Passive solar dryers integrated with thermal energy storage (TES) materials can reduce the intermittent drying of agricultural products, improve the drying efficiency, and reduce the drying time.[15] TES materials store thermal energy during the day when there is enough solar energy and discharge it when sunlight is unavailable, ensuring continuous drying of agricultural products.[16] Most of the previous studies have primarily focused on the application of phase change materials (PCM) for agricultural drying applications.[17] The key issue with using PCM is that the temperature range of the process during charging and discharging must be tightly constrained. The intermittent availability of sun radiation makes it challenging to meet this need in simple solar dryers. The use of sensible thermal energy storage (STES) materials, like gravel, granite, sandstones, limestone, and soapstone, has been relatively less explored, despite their effectiveness in simple solar dryers. STES materials offer advantages, including natural availability, cost effectiveness, improved efficiency, shorter drying times, preservation of product quality, and non-toxicity.[18−21]

Soapstone, in particular, possesses good thermal conductivity and has been used for various purposes due to its thermal properties and historical availability. Kakoko, Jande, and Kivevele,[22] conducted experimental investigation of soapstone and granite as energy storage materials and found that soapstone rock performed better than granite as a TES material for solar drying technology and solar power generation applications. According to Pirinen,[23] soapstone rock has a higher density of about 2.98 g/cm^3, which is higher compared to other natural rocks, and a specific heat capacity ranging 0.9−1.1 kJ/kg °C that is about 20% more than that of other typical natural rocks. However, despite its good thermal storage properties, the application of soapstone as a TES material for agricultural product drying remains relatively understudied. Thus, this work aims to investigate the potential of soapstone integration as a TES material to reduce intermittence in a constructed passive solar dryer. A novel solar dryer integrated with soapstone as a TES material was developed and evaluated for its performance by drying 50 kg of fresh pineapples and carrots. The experiments were carried out in two modes: dryer with TES materials and dryer without TES materials, and the results were compared with that of OSD. The dryer's performance was evaluated in terms of drying parameters (temperature, relative humidity, and airflow), thermal/drying efficiency, charging and discharging of soapstone (storage efficiency), solar collector efficiency, and proximate analysis of dried products compared to open sun-dried products. This study therefore seeks to contribute to sustainable and efficient agricultural drying practices in the regions with limited resources and intermittent solar availability.

2. MATERIALS AND METHODS

2.1. Experimental Setup. A solar dryer integrated with TES materials was designed and fabricated at the workshop of the Mechanical Department, Arusha Technical College (ATC), Arusha-Tanzania. The dryer was then relocated to the Tanzania Horticultural Association (TAHA) Farmers Training Centre in Tengeru, Arusha, for experimentation and data collection. The dryer consists of three subsystems: solar collectors, drying chamber, and energy storage (soapstone), as seen in Figures 1−3. The materials used for the fabrication of

Figure 1. Photograph of the solar dryer placed at the TAHA Farmers Training Center, Tengeru-Arusha.

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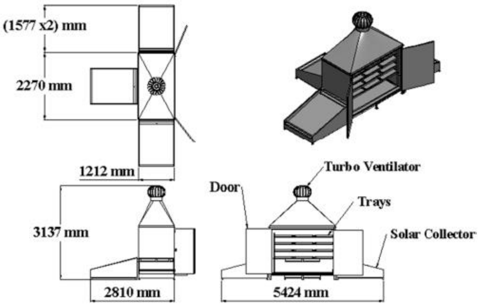

Figure 2. Schematic diagram of the developed solar dryer.

Figure 3. Photograph of a solar dryer collector with and without TES.

the solar dryer were purchased from the local market; some of the materials used are mild steel sheets of 1.5 mm thickness, aluminum sheets of 1.5 and 0.5 mm, a hollow section of 40 × 25 mm, a clear transparent glass of 6 mm thickness, a wind ventilator of diameter 400 mm, a flat bar of 25 × 3 mm, plastic mesh, gasket, reverts, bolts, and nuts, and soapstones as TES materials. Soapstones were collected from the Craton geotectonic setting in the Dodoma Region, located in the central part of Tanzania. The solar dryer, including the drying chamber and solar collectors, was made with a double-wall separated by insulation materials (fiberglass) of 2.5 cm thickness to prevent heat transfer between the inside and outside environment. For food safety measures, the interior surface of the drying chamber was made of an aluminum sheet of 1.5 mm thickness. In contrast, the exterior surface was made of a mild steel sheet of 1.5 mm thickness. The designed capacity of the solar dyer is 50 kg per batch, and the dimensions of the drying chamber were 2.27 m (L) × 1.2 m (W) and 1.5 m (H). Fifteen trays were made from an aluminum sheet of 1.5 mm to carry the drying materials. The length and width of each tray were 1.018 and 0.65 m, respectively, and each tray was designed to carry 3.4 kg of vegetables or fruits. A small chamber of 2.27 m (L) × 1.2 m (W) and 0.5 m (H) was provided below the drying chamber to allow the use of another source of energy, such as biogas or liquefied petroleum gas (LPG) during severe weather conditions, especially when sun radiation is not available for drying. To facilitate air movement inside and outside the drying chamber, a wind ventilator with a diameter of 400 mm was installed at the top of the dryer.

The solar dryer was designed with three collectors to ensure the capture of solar radiation throughout the day. The dimensions of the solar collector are 1.6 m (L) × 1.2 m (W). The inside of the solar collector was coated with black paint, enabling it to soak up solar radiation and retain thermal energy. The soapstones were positioned at a depth of 0.12 m from the bottom of the solar collector and covered with a 0.5 mm thick aluminum plate that had been coated in black paint by using tarmac/tar to effectively absorb solar radiation. The weight of the TES materials (soapstone) placed inside the solar collectors, as seen in Figure 3, was determined using a weigh scale and found to be 220 kg for each solar collector. An air vent of 0.08 m depth and 1.2 m wide with an adjustable gate that allowed airflow adjustments was positioned between the absorber plate and the collector glass of the solar collector. The design of the air vent was made according to Raju, Reddy, and Reddy,[8] who suggested at least a 5 cm air vent for hot climates. The top of the solar collector was covered by a clear glass of 6 mm thickness to transmit solar radiation to the collector. The tilt angle of the solar collector was designed to receive sufficient amounts of solar radiation according to ref 24 and was found to be 13.4°. Figures 1−3 show the photograph and sketch of the solar dryer; the summary of the specification of the solar dryer is presented in Table 1.

Table 1. Summary of the Specifications of the Solar Dryer

descriptions	unit	value
volume of the of drying chamber	m^3	3.96
thickness of the solar collector glass	m	0.006
thickness of the aluminum absorber plate	mm	0.5
insulation thickness (fiberglass)	m	0.025
capacity of the dryer	kg	50
surface area of the solar collector	m^2	1.8
volume of the collector occupied by TES materials	m^3	0.18
depth of the collector air vent (adjustable)	cm	0−8
weight of the TES in each collector	kg	220
surface area of the tray	m^2	0.65
loading capacity of the dryer	kg	4
distance between trays	m	0.24
tilt angle of the collector		13.4°

2.2. Experimental Procedure. The experiments were conducted at the TAHA Farmers Training Centre in Tengeru-Arusha Region, Tanzania. The dryer was tested for drying pineapples (*Ananas comosus*) and carrots (*Daucus carota*). Pineapples, botanically classified as fruits, and carrots as root vegetables, are essential products in Tanzania's economy and a source of nutrition. However, they are vulnerable to postharvest loss, especially during peak seasons. The fresh samples were purchased from a local market in Arusha Region, Tanzania. The carrots weighed about 65 g on average, whereas the pineapples weighed roughly 1.5 kg. Following washing, the samples were peeled and then cut into homogeneous slices approximately 3 mm thick, which is regarded as an appropriate thickness for successful drying based on previous research.[25] For carrots, a simple hand vegetable slicer was used to make circular slices with an average diameter of around 2.6 cm and a weight of about 3 g. Pineapples were cut longitudinally into four parts, and each part was manually sliced. The samples were not pretreated. A total of 50 kg of each type (carrots and pineapples) was sliced and dried using the developed solar dryer and OSD until their ultimate moisture content was less than 10% wet basis (w.b.).

The drying time, solar radiation, weight reduction, temperature, and relative humidity were recorded every 30 min. Inside the soapstone compartment, three SSN-11E USB temperature

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Table 2. Measuring Instruments and Uncertainties in Measurements

S/N	instrument	range	accuracy	resolution	error (%)	uses
1	SSN-11E USB temperature data logger meter	−40 to 125°C	±0.5°C	±0.1°C	0.01414	temperature measurement
2	SSN-22E USB temperature humidity data logger meter	0–100% RH	±0.3 RH	±0.1 RH	0.01414	humidity measurement
		−40 to 125°C	±0.3°C	±0.1°C	0.01414	temperature measurement
3	TES 132 solar power meter	2000 W/m²	±10 W/m²	0.1 W/m²	0.01414	solar radiation measurement
4	kestrel 3000 wind meter	0.6–40 m/s	±0.1 m/s	0.05 m/s	0.07071	wind measurement
5	FF1976 constant digital weighing scale	0–40 kg	0.14 g	0.1g	0.01414	weight measurement

data logger probes were positioned to monitor the soapstone's temperature. At both the inlet and outlet of the solar collectors, data logger meters were placed to measure the temperature and relative humidity (SSN-22E USB temperature humidity data logger meter). Inside the drying chamber, three similar data logger meters were positioned to measure the temperature and relative humidity. A Kestrel 3000 wind meter was used to measure the airflow (inside and outside the drying chamber), and an FF1976 constant digital weighing scale was used for measuring the weight of the products. A TES 132 solar power meter was located on the solar collector for measuring the solar irradiance.

The drying experiments were conducted under two operating modes: a solar dryer with load but without TES and a solar dryer with load and TES materials. Data were collected on three consecutive days in each mode, and the average values were determined. Data collection was performed from January to March 2023.

2.3. Error and Uncertainty Analysis. In most cases, measuring instruments are subjected to errors, regardless of their precision and accuracy. The two major causes of these uncertainties are measuring devices, sometimes known as systematic errors, and measurement skills or random errors. Uncertainty assessment is crucial for designing and implementing the experiment.[26] The total errors were calculated by using eq 1 according to Gulcimen, Karakaya, and Durmus.[27] Table 2 shows the instruments used for the measurements and their uncertainty assessments

$$w_{\mathrm{th}} = \sqrt{(X_1)^2 + (X_2)^2 \ldots\ldots(X_\infty)^2} \quad (1)$$

where X = independent variables affecting measurements.

The independent variables affecting measurements were determined by using eq 2 according to AR and Veeramanipriya[28]

$$w_{\mathrm{n}} = \sqrt{(W_{\mathrm{instument}})^2 + (W_{\mathrm{reading}})^2} \quad (2)$$

The overall errors in the measurement of different parameters are given by eq 3, which is a simplified equation from eq 1

$$w_{\mathrm{total}} = \sqrt{(W_{\mathrm{temperature}})^2 + (W_{\mathrm{humidity}})^2 + (W_{\mathrm{solar\ radition}})^2 + (W_{\mathrm{wind}})^2 + (W_{\mathrm{w\ scale}})^2} \quad (3)$$

The overall uncertainties in the measuring devices and reading errors were calculated according to eq 3 and found to be ±0.0701%. This value is small compared to the acceptable range of ±10%, according to Choi, Kikumoto, Choudhary, and Ooka.[29]

2.4. Performance Analysis. The performance of the solar dryer integrated with soapstone as a TES material was analyzed by determining the sensible heat energy storage of TES materials (E), storage efficiency of TES materials (η_s) weight of water evaporated from the product (M_w), drying rate (D_r), thermal efficiency (η_t) collector efficiency (η_c), and saving of drying time (%). In addition, a comparative evaluation of drying time, temperature, and relative humidity by using TES materials, without TES materials, and OSD were conducted.

2.4.1. Amount of Sensible Heat Energy Storage. The amount of energy storage by materials is an essential parameter in selecting TES materials because it describes the amount of heat energy that can be stored in the materials at a particular time. The amount of energy storage was estimated by eq 4 according to Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam[18]

$$E = M_a C_p (T_f - T_i) \quad (4)$$

where E = energy storage (J), M_a = weight of storage materials (kg), C_p = specific heat capacity of soapstone (J/kg °C), T_i = temperature of the storage materials at time t (°C), and T_f = temperature of the storage material in the proceeding time (°C).

2.4.2. Storage Efficiency. The storage efficiency of TES materials (η_s) is the ratio of the discharged energy to the charging energy from the TES materials; it was calculated by using eq 5 according to Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam[18]

$$(\eta_s) = \frac{E_{\mathrm{discharge}}}{E_{\mathrm{charge}}} \quad (5)$$

2.4.3. Weight of Water Evaporated. The weight of water evaporated is the amount of water evaporated from the product during the drying process. Fruits and vegetables contain a great amount of water as compared to solids. The weight of water evaporated was calculated using eq 6 according to Fudholi, Sopian, Alghoul, Ruslan, and Othman,[30] Santanu Malakar,[31] and Suleiman, Pogrebnoi, and Kivevele[32]

$$M_w = \frac{M_o(M_i - M_f)}{100 - M_f} \quad (6)$$

where M_o = initial mass of the products, M_i = initial moisture content of the product on wet basis (%), and M_f = final moisture content of the product on wet basis (%).

2.4.4. Drying Rate. Drying rate is the ratio of moisture evaporated from the product over time. The drying rate of the products was estimated using eq 7 according to Hasibuan, Yahya, Fahmi, and Edison[33]

$$\mathrm{DR} = \frac{\mathrm{M_w}}{t} \quad (7)$$

where M_w = total mass of water evaporated from the drying products (kg), and t = drying time (h).

2.4.5. Dryer Thermal Efficiency. The dryer thermal efficiency is the ratio of energy required to evaporate water from the drying product to the energy supplied by the dryer.

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The thermal efficiency of the dryer was calculated using eq 8, as proposed by Ayyappan, Mayilsamy, and Sreenarayanan[21]

$$\eta_t = \frac{M_w h_{fg}}{A_c \times I} \quad (8)$$

where M_w is the total mass of water evaporated from the drying products (kg), h_{fg} is the latent heat of vaporization of water (kJ/kg), obtained from the saturation properties for steam temperature table, A_c is the area of the solar dyer (m^2), and I is the solar irradiance (W/m^2).

2.4.6. Collector Efficiency. The ratio of useful heat gained per unit aperture area to the average incidence radiation of the collector is the collector efficiency. The efficiency of the collector with energy storage (η_c) was calculated using eq 9 and as reported by Singh, Singh, Akhtar, and Khajuria[34]

$$(\eta_c) = \frac{M_a c_a (T_c - T_a)}{A_c I} \quad (9)$$

where M_a = mass of air flowing in the collector per unit time (kg/s), C_a = specific heat capacity of air (kJ kg^{-1} K^{-1}), A_c = collector area (m^2), and I = solar irradiance (W/m^2).

The mass of air flowing in the collector per unit time (M_a) was calculated by using eq 10 according to Singh, Singh, Akhtar, and Khajuria[34]

$$M_a = \rho_a V_a C_v \quad (10)$$

where V_a = velocity of air (m/s), ρ_a = density of air (m^3/kg), and C_v = cross-sectional area of air vent (m^2).

2.4.7. Saving in Drying Time. Saving in drying time (%) is the time saved by using a solar dyer compared to OSD. It was calculated using eq 11, according to Fudholi, Othman, Ruslan, and Sopian.[35]

$$\text{Saving in drying time (\%)} = \frac{t_{OS} - t_{SD}}{t_{OS}} \quad (11)$$

where t_{OS} = time taken in (h) to dry a product under open sun, and t_{SD} = time taken in (h) to dry a product in a solar dryer.

2.5. Proximate Analysis. Even though drying is a fundamental process for food preservation, it has been reported to slightly change the quality of the dried products, such as color, flavor, and nutrients.[36,37] However, according to Bhardwaj, Kumar, Chauhan, and Kumar,[20] drying agricultural products using solar dryers integrated with TES materials has been reported to retain the nutritional values. Therefore, proximate analysis was conducted to determine whether there was a loss of nutritional composition in the dried products in terms of moisture content, ash content, crude fiber, fats content, protein, vitamins, and minerals. The assessment was conducted for pineapples and carrots.

2.5.1. Determination of Moisture Content. Determining the moisture content helps us to understand the water level available in the product before and after drying. The gravimetric oven drying method determined the moisture content according to the Association of Official Analytical Chemist (AOAC) method.[38]

Exactly 5 g of paste sample was accurately weighed in clean and dry Petri dishes and then dried in an oven at 105 °C for 24 h until the content showed no further change in weight. The Petri dish was placed in a desiccator for 30 min to cool. After cooling, the final weight was recorded, and the moisture percentage was calculated using eq 12

$$\text{\% moisturecontents (on wet basis)} = \frac{m_i - m_f}{m_i} \times 100 \quad (12)$$

2.5.2. Determination of Ash Contents. Ash content determination is the first step in sample preparation for a particular analysis. A dry ash method was used to determine ash content according to AOAC methods.[38] A clean empty crucible was placed in a muffle furnace at 550 °C for 1 h to ensure that all possible impurities on the surface of the crucible were burned off. The device was placed in the desiccator for 30 min for cooling, and the weight of the empty crucible was recorded. Exactly 5 g of the sample was placed in the crucible and then placed in the muffle furnace. The ultimate weight was determined after the crucible and its contents had been heated in the muffle furnace for 24 h and cooled in the desiccator. The percentage of ash contents was determined by using eq 13

$$\text{\% ash content} = \frac{\text{weight of ash}}{\text{weight of sample}} \times 100\% \quad (13)$$

2.5.3. Determination of Crude Fiber. The crude fiber analysis involves two stages of digestion of acid and alkaline solutions, using the method described by the AOAC methods.[38] The percentage of fiber was calculated using eq 14

$$\text{Crude fiber (\%)} = \frac{\text{weight of residual} - \text{weight of ash}}{\text{Weight of sample}} \times 100\% \quad (14)$$

2.5.4. Determination of Protein. Protein is one of the essential foods in our body; it provides crucial elements, such as amino acids, for the growth and maintenance of our cells and tissues. When agricultural products are dried, especially in higher temperatures, they lose some nutrients.[39] Protein concentration was evaluated using the Kjeldahl nitrogen method, as defined by AOAC methods.[38] The method involves three steps: digestion, distillation, and titration. Based on this method, exactly 5 g of samples was digested by heating with concentrated sulfuric acid in the presence of the Kjeldahl catalyst to ammonium sulfate. The digested mixture was naturalized with NaOH, and nitrogen was distilled off and trapped in a boric acid solution. The amount of nitrogen was quantified by titration with an HCl solution. The percentage of nitrogen contents was determined by using eq 15. The obtained nitrogen was multiplied by conversion factor 6.25, as shown in eq 16

$$\text{Nitrogen}\left(\%, \frac{w}{W}\right) = \frac{\text{volume of acid (ml)} \times \text{molarity of acid (mol l}^{-1}) \times 14\ (\text{g mol}^{-1})}{\text{weight of sample (g)} \times 100} \quad (15)$$

$$\text{Nitrogen (\%)} = \text{nitrogen } (\%, w/W) \times \text{protein factor} \quad (16)$$

2.5.5. Determination of Fat. Fat content was determined by Soxhlet method as described by AOAC methods.[38] A precisely 5 g sample was placed into the extraction thimble and assembled into the Soxhlet apparatus. Petroleum ether (70 mL) was used for the extraction process in three phases in a fat analyzer machine. The boiling phase was 15 min, the rinsing phase was 30 min, and the petroleum ether recovery phase was 10 min. The remaining petroleum ether was then evaporated in the oven. Preweighed cups containing fat were dried in an oven

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at 105 °C for 1 h to evaporate any remaining petroleum ether and then cooled in a desiccator for 30 min and reweighed. Percentage fat was calculated by using eq 17

$$\% \text{ fats} = \frac{\text{weight of crude fat}}{\text{weight of sample}} \times 100\% \quad (17)$$

2.5.6. Determination of Total Carbohydrates. Total carbohydrate was determined by taking the difference of the sum of all total proximate compositions from 100%.

$$\text{Total carbohydrate } \% = 100\% - (\text{ash content } \% - \text{protein } \% + \text{fat content } \% + \text{crude fiber } \% + \text{moisture content} \quad (18)$$

2.5.7. Determination of Minerals. Vegetables and fruits are sources of minerals for human health. Minerals play important roles in building and maintaining bones, muscles, and brain to work properly. Mineral elements which were analyzed were calcium (Ca), sodium (Na), magnesium (Mg), potassium (K), and phosphorus (P). One gram of sample was taken in a conical flask, and 10 mL of nitric acid (HNO_3) was added. The mixture was boiled for about 20 min to almost dryness and then cooled, filtered using Whatman filter paper number 1, and diluted with 100 mg of water. An atomic absorption spectrophotometer was used to analyze the minerals separately.

2.5.8. Determination of Vitamins. Vitamins are very much essential for the growth and development of our body. In this study, vitamins A and C were determined using AOAC methods.[38]

3. RESULTS AND DISCUSSION

3.1. Evaluation of Drying Parameters. The variability of sun irradiation falling on the ground surface impacts the performance of the solar dryer. The graph in Figure 4 depicts a considerable fluctuation in the intensity of solar energy input over time. The average minimum and maximum sun irradiation levels ranged from 160 to 1140 W/m^2, respectively. The minimum irradiation was observed during the morning and evening, whereas the maximum irradiation was observed around 1.00 p.m. It can be observed that the intensity change of the solar energy input is relatively large crossing the time; this could be attributed to the prevalence of diffuse radiation and cloud cover in equatorial locations, as highlighted by Dazhi, Jirutitijaroen, and Walsh et al. (2012)[40] in their study on estimating the hourly solar irradiance using the cloud cover index. Nonetheless, the integration of TES materials within the collectors reduces the energy swings caused by solar irradiance.

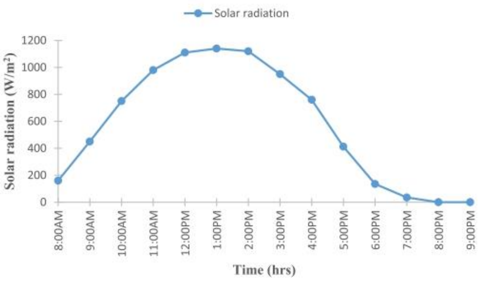

Figure 4. Variation of solar radiation with time.

Temperature plays a very important role in product drying. Figure 5 shows comparisons of temperature variation inside the drying chamber when the dryer is integrated with TES, and without TES materials, as well as ambient temperature with time. The maximum temperature was recorded at 1.00 p.m during the time of peak solar irradiance. The maximum temperature recorded for the dryer with TES materials was 62 °C, that without TES material was 61 °C, and the ambient temperature was 33 °C. The use of TES materials maintained a uniformly higher temperature in the drying chamber compared with the one without TES materials. For example, from Figure 5, at 7:00 p.m. when the ambient temperature was 28 °C, the temperature in the drying chamber with the TES material was observed to be 44 °C, and it continued to decrease gradually until 12:00 p.m. when the drying chamber temperature was 27 °C and the ambient temperature was 23 °C. TES materials prolonged the drying temperature about 3−4 h after sunset. Therefore, soapstone materials play an important role in storing solar energy during the day and release it later, hence extending the drying time. The results are in agreement with those of Bhardwaj et al. (2020) who evaluated the performance of a solar dryer integrated with the combination of STES and PCM for drying chill. In that particular research, it was found that PCM provided backup for about 6 h, whereas STE provided 2−3 h after sunset.

Relative humidity is another important parameter in the product drying process. Figure 6 shows the comparative analysis of the variation in air relative humidity inside the drying chamber for the dryer with TES materials and without TES materials as well as ambient with time. It is clear that the relative humidity inside the drying cabinet when the dryer is integrated with TES and without TES materials is relatively less compared with the ambient relative humidity. However, the relative humidity with TES materials is considerably less compared to the mode of dryer without TES materials. The average ambient relative humidity ranged from 41 to 77% during the day and night, respectively. The minimum relative humidity in all the drying methods was recorded during the day around 1:00 p.m and the maximum around 12:00 p.m during night. The relative humidity in the drying chamber without TES materials was about 25% during the day and 76% during night, whereas in the drying chamber with TES materials, it was about 9% during the day and 55% during night. It is evident that the relative humidity inside the drying chamber when the dryer is integrated with TES materials is lower than the one without TES materials and open sun. The lower relative humidity is attributed to the presence of TES materials which maintain higher temperature and hence lower relative humidity in the drying chamber. These results are in agreement with those of Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam,[18] who conducted experimental evaluation of an indirect solar dryer with sensible heat storage materials and reported that storage materials increased the drying temperature and reduced the relative humidity.

The use of TES materials involves charging of thermal materials when solar energy is available and discharging them when solar energy is not available. The amount of thermal energy stored in the soapstone during charging was determined using eq 4 and found to be 8.8 and 6.5 MJ during charging and discharging, respectively. Storage efficiency was determined

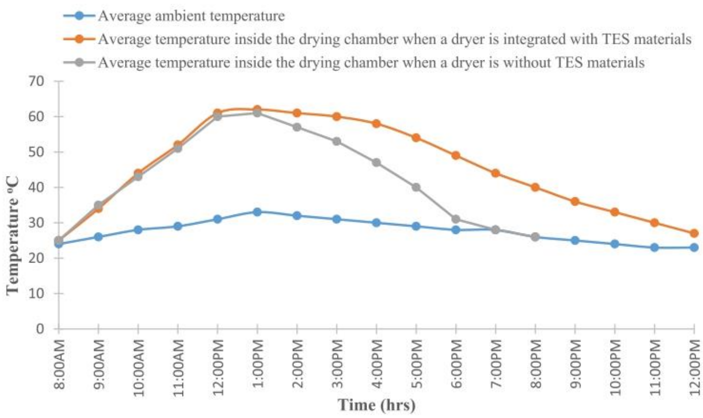

Figure 5. Variation of temperature with time.

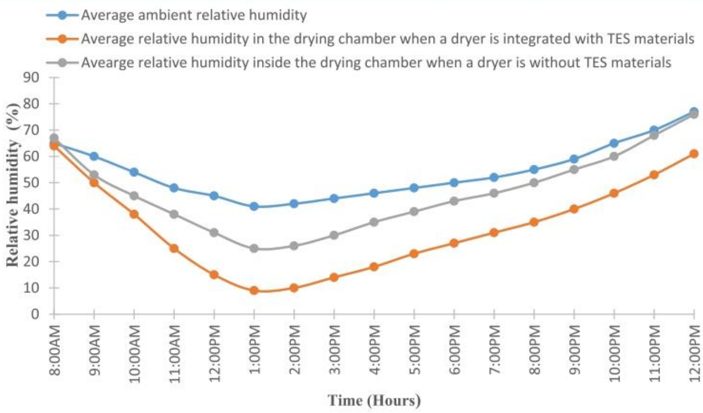

Figure 6. Variation of relative humidity with time.

according to eq 5 and was found to be 74.5%. The obtained results are in good agreement with the one reported by Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam,[18] who conducted an experimental evaluation of indirect solar dryer agricultural products using limestone and bench sand as TES materials. The charge and discharge energies for limestone were 2.4 and 2.0 MJ, respectively, whereas for beach sand, it was 5.9 MJ for charging and 4.1 MJ for discharging. The storage efficiency for limestone was 84.2%, whereas for beach sand, it was 70.3%.

3.1.1. Performance Evaluation of the Developed Dryer. The developed dryer was tested for drying pineapples (fruit) and carrots (vegetable); their initial moisture content was lowered from 90 and 88%, respectively, to 10% wet (w.b). The weight of water evaporated from 50 kg of drying products was calculated using eq 6 and found to be 44.4 kg for pineapple and 43.4 kg for carrot. The weight of dried products removed from the dryer was 5.5 and 6.6 kg for pineapples and carrots, respectively. Figures 7 and 8 show the drying curves for pineapples and carrots using solar radiation with TES materials, without TES materials, and OSD. In all of the drying methods, the drying rate was fast at the beginning and continued to decrease with time. The drying times for pineapples in the dryer with TES, without TES, and OSD were 13, 24, and 52 h, respectively, whereas the drying times for carrots in the dryer with TES, without TES, and OSD were 12, 23, and 50 h, respectively. The application of TES materials (soapstone) maintained a higher drying temperature in the range 62−30 °C in the drying chamber and a low relative humidity in the range 9−53%, which reduced the drying time. In comparison with previous studies, the result is in agreement with the findings of Ahmad and Prakash[26] who dried tomato flakes in a greenhouse dryer integrated with TES materials in which it was reported that the tomato flakes were reduced from 96 to 9.10% (wet basis) in 13 h. The results are also in good agreement with the findings reported by Kareem, Habib, Ruslan, and Saha[41] who investigated the performance of a multipass solar air heating system integrated with gravel as TES materials for drying Rosella, and the moisture content of Rosella was reduced from 85.6 to 9.2% (wet basis) in 14 h.

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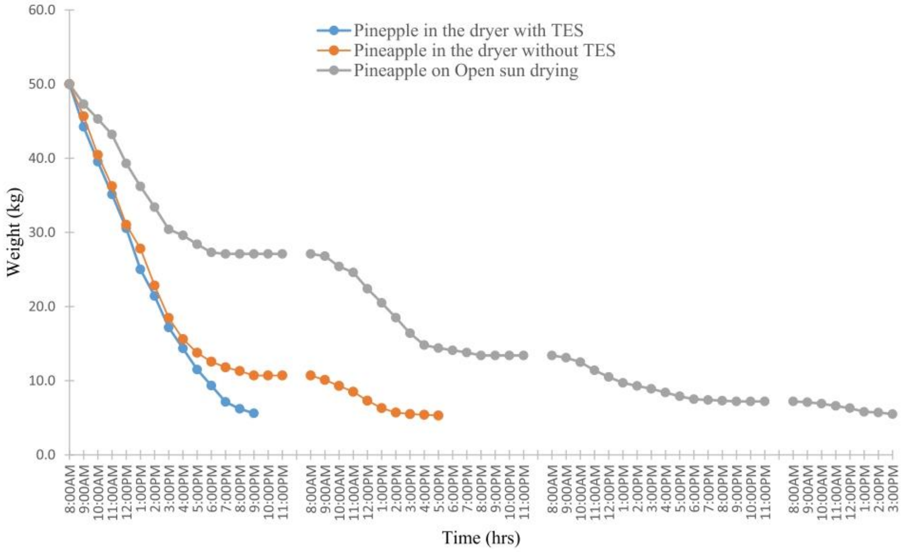

Figure 7. Weight change with time of pineapples in a solar dryer with TES materials and without TES materials and OSD.

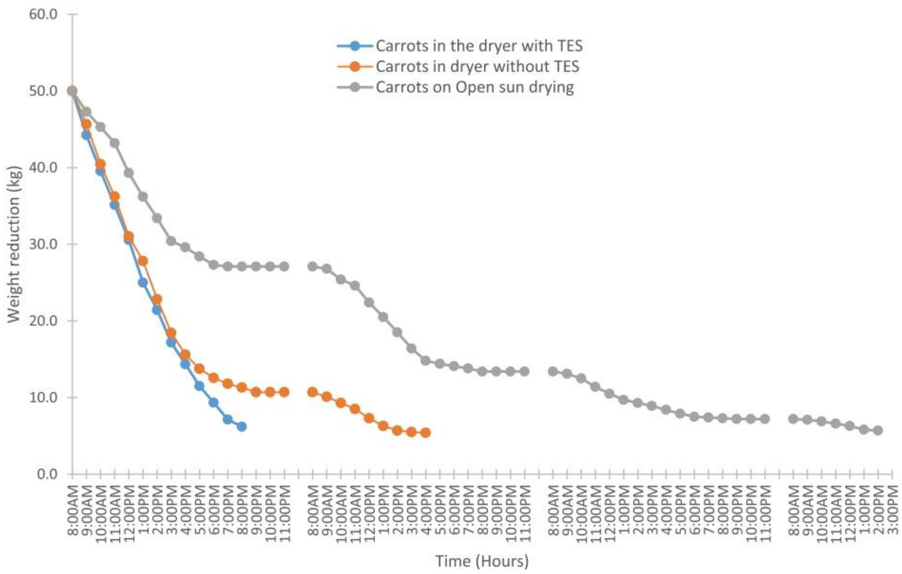

Figure 8. Weight change with time of carrots in a solar dryer with TES materials and without TES materials and OSD.

The drying rate which was calculated using eq 7 was found to be 3.4 kg/h for pineapples and 3.6 kg/h for carrots when a dryer integrated with TES materials was used, whereas for the dryer without TES materials, it was about 1.85 kg/h for pineapples and 1.88 kg/h for carrots. The drying time for ODS was 0.86 kg/h. The thermal efficiency of the dryer was calculated using eq 8 and found to be 45% with TES materials and 38% without TES materials and 25% for OSD. The results are consistent with that of Mugi, Das, Balijepalli, and Chandramohan,[16] who reported that the thermal efficiency for the majority of solar dryers combined with TES materials ranged from 9.9 to 58.2%. The collector's efficiency with TES

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Table 3. Comparison of the Performance Results of Solar Dryers with Some Previous Published Works

				drying time (h)			dryer thermal efficiency (%)			collector efficiency (%)		
S/n	types of solar dryer	loading capacity of the product	types of rock used	TES	no TES	OSD	TES	no TES	OSD	TES	no TES	references
1	hybrid solar dryer integrated with TES	2.5 kg of sliced *Carica papaya* per batch	gravel	5	6	11	34.5	30.2	19.3			28
2	multipass solar air heating collector dryer	75.2–81.3 kg of Roselle	granite	14		35	36.22			64.08		41
3	solar dryer integrated with packed bed TES system	10 kg of sliced orange	pebble	7	7.2		54.71–68.37	50.18–66.58				45
4	indirect solar dryer integrated with TES materials	0.8959 kg of tomato slices	limestone	22	25		12.57	8.41				18
		0.9641 kg of sliced tomato	beach sand	23	25		11.02	8.37				
5	solar dryer integrated with STE and PCM	9 kg of chill	gravel	21	96	150	15.62			78.02		20
6	triple-pass solar dryer	4 kg of potato	sand	4.5		5	53.57			45		42
7	indirect solar dyer integrated with TES materials	4 kgof bitter gourd	pebble	7		10	19			22		43
8	forced convection solar dryer	60 kg of copra	sand	82		168				24		44
9	greenhouse dryer	4 kg of tomato flakes	gravel	13								26
10	convectional solar dryer using TES materials	5 kg of Vitis vinifera	sand	28	53	58	40					46
		2 kg of momordica	sand	5.3	7	10	42					
11	greenhouse solar dryer integrated with TES materials	coconut	rock	53		174				11.65		21
		coconut	concrete	78		174				9.5		
		coconut	sand	66		174				11		
12	solar dryer integrated with TES materials	50 kg of pineapples and 50 kg carrots	soapstone	13	24	52	45 38	25		43	36	current study

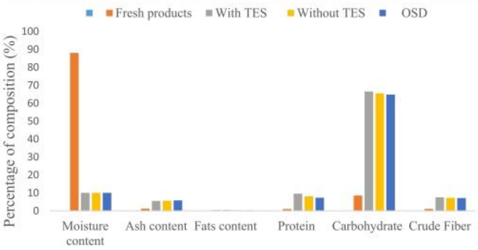

Figure 9. Graph of proximate analysis for pineapples.

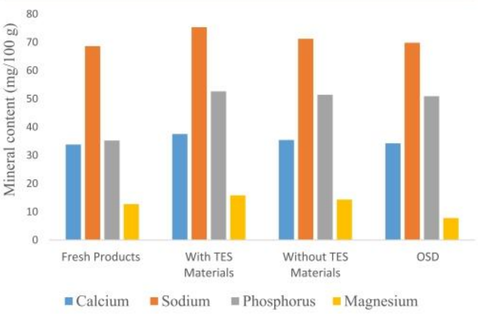

Figure 10. Graph of proximate analysis of minerals for carrots.

materials was calculated using eq 9 and found to be 43%. The obtained efficiency agrees with that of Kesavan, Arjunan, and

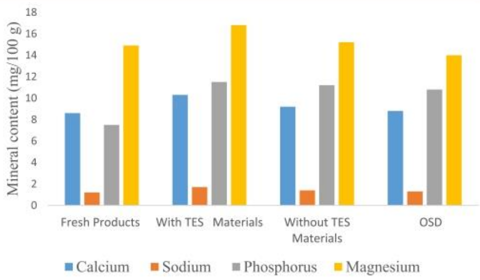

Figure 11. Graph of proximate analysis of minerals for pineapples.

Vijayan,[42] in which it was reported to be 45% for a triple-pass solar dryer integrated with sand as TES material. However, collector efficiency in this research was found to be higher as compared to 22% reported by Vijayan, Arjunan, and Kumar[43] for bitter gourd drying using a solar dryer integrated with pebble as the TES and 24% reported by Mohanraj and Chandrasekar[44] who used solar dryer integrated with sand as the TES material for drying copra. The differences in the TES materials used may have contributed to the differences.

Saving in drying time (%) was calculated using eq 12 and was found to be 75%. This means 75% of time can be saved when using the developed solar dryer integrated with the TES material compared to OSD. The results of this study are slightly better as compared to that of Ayyappan, Mayilsamy, and Sreenarayanan[21] who reported that the percentage of saving time for a solar dryer integrated with TES for coconut drying with concrete was 55%, that with sand was 62%, and

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Table 4. Results of Proximate Analysis for Vitamins

parameters	fresh products (control)		with TES materials		without TES materials		OSD	
	carrot	pineapple	carrot	pineapple	carrot	pineapple	carrot	pineapple
vitamin C (mg/100 g)	5.8	47.3	5.6	45.8	5.4	43.5	5.1	40.2
vitamin A (mg/100 g)	880.5	55.7	897.2	68.1	891.8	58.2	885.6	56.5

that with rock was 69%. The difference is caused by the difference in the drying time, which took 78, 66, and 53 h when a dryer is integrated with concrete, sand, and rock, respectively, whereas OSD took 174 h.

The performance comparisons of solar dryers with TES and without TES materials and OSD from the present study and various published works are summarized in Table 3. The results of this study are in good agreement with previous studies, such as the findings reported by AR and Veeramanipriya,[28] who compared the performance of solar dryers integrated with TES, without TES, and open OSD and found that the solar dryer integrated TES materials performed better as compared to the one without TES materials and OSD.

Table 3 shows the comparison of the performance results in terms of drying time, thermal efficiency, and collector efficiency of the solar dryer integrated with different natural rocks such as gravel, granite, pebble, and sand. It can be seen clearly that the drying time, thermal drying efficiency, and collector efficiency for a solar dryer integrated with TES materials is higher compared to that without TES and OSD. For example, the drying time for pineapple from this study when a dryer uses TES materials is 13 h, that without TES materials is 24 h, and OSD is 52 h. The dryer thermal efficiency when a dryer uses TES materials is 45%, without TES materials 38%, and OSD is 25%. The collector efficiency when a dryer uses TES materials is 43% and that without TES materials 36%. These results are inconsistent with the results presented in Table 3 (previously published works).

3.2. Proximate Analysis of Dried Products. One of the most desirable aspects during the drying process is the retention of nutritional value of the dried products. Figure 9 shows a comparative analysis of nutritional contents (carbohydrate, crude fiber, protein, fats, and ash contents) for fresh and dried products using a dryer integrated with TES materials, without TES materials, and OSD. All the drying methods reduced moisture to a desirable level of about 10%, which is safe for increasing the product shelf life. The results indicate that all the drying methods increased the concentrations of nutritional value in the dried products because of the removal of water from the fresh products. This implies that a similar amount of products has more concentrated amounts of the same nutrients and calories as compared to fresh products. According to Mongi and Ngoma,[37] the drying process decreases the moisture contents which lead to an increase in the soluble concentration.

Carbohydrate showed the highest concentration in the dried products, followed by protein, crude fiber, and ash, and the least was observed in the fat contents for all the drying methods, as seen in Figure 8. With regard to the drying methods, drying products by using a dryer integrated with TES materials showed the highest concentration in nutrient composition, followed by a dryer without TES materials, and the least was observed with OSD. For example, the carbohydrate composition for the dryer integrated with TES materials was 66.5%, whereas that without TES and OSD was 65.4 and 64.8%, respectively. Likewise, for proteins, the compositions were 9.53% for the dryer with TES materials, whereas for the dryer without TES and OSD, they were 8.1 and 7.3%, respectively. This is because the integration of TES materials evaporates moisture quicker at uniform temperature.[20] This result is in agreement with previous studies by Seidu, Bobobee, Kwenin, Frimpong, Kubge, Tevor, and Mahama,[47] who studied the preservation of indigenous vegetables by solar drying technology. They found that solar drying reduced the moisture content and increased the concentration of protein, fiber, ash, and fat contents compared to fresh products. Lakshmi, Muthukumar, and Nayak[12] conducted experimental investigation on active solar dyers integrated with TES materials for drying black pepper, in which it was reported that drying reduced moisture contents and improved protein, fiber, ash, carbohydrate, and fat concentrations in the dried as compared to fresh products. Baloch, Xia, and Sheikh[48] studied proximate and mineral compositions of dried cauliflower by using OSD and cabinet dehydration. They found that drying reduced moisture contents, and the concentrations of protein, fiber, ash, carbohydrate, and minerals in the dried products were higher as compared to fresh ones.

Proximate analysis was also conducted for selected minerals such as calcium, sodium, phosphorus, and magnesium, as depicted in Figures 10 and 11 for carrots and pineapples, respectively. All the drying methods increased the concentrations of minerals as compared to fresh products because of the removal of water from the fresh sample. However, mineral concentration was relatively higher using a solar dryer integrated with TES materials, followed by the dryer without TES materials and OSD. The results align with the results reported by Mohammed,[49] who conducted proximate analysis for drying mangoes and pineapples using different solar drying technologies and found that all the solar drying methods increased the concentration of mineral contents compared to the fresh products.

The concentration of vitamin C was found to be reduced in all of the drying methods; however, a significant increase of concentration of vitamin A was observed as compared to fresh products, as shown in Table 4. For example, the concentration of vitamin C in a fresh carrot was 5.8 mg/100 g, whereas that with TES materials was 5.6 mg/100 g, without TES materials was 5.6 mg/100 g, and OSD was 5.1 mg/100 g. The reduction in the concentration of vitamin C was slightly smaller when using a solar dryer integrated with TES materials compared to the solar dryers without TES materials and OSD. The reduction in vitamin C is due to its sensitivity to heat. Vitamin C is very sensitive to heat; heat easily destroys vitamin C because it is a water-soluble vitamin (Eze and Ojike[50]).

Table 5 shows the comparison of the proximate results of the solar dryer for some agricultural products from some previous studies. It can be seen from the table that all the drying methods reduced moisture and increased the concentrations of nutritional values in the dried products because of the removal of water from the fresh products. In

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Table 5. Comparison of the Proximate Results of Solar Dryers of Some Previous Published Works

S/N	types of solar dryer	product analyzed	drying temperature (°C)	parameters analyzed	findings	reference
1	cabinet mixed-mode dryer (CMG) and tunnel dryer (TD)	mango	30–55 in CMG and 30–73 in TD	moisture, protein, fat, crude fiber, ash, carbohydrate, and minerals (Ca, Fe, K, Na, and P)	the two drying methods reduced moisture, protein, fats, crude fibers, and minerals as compared to fresh products, and more loss was observed by using the TD method; however, carbohydrates were higher in dried as compared to fresh products	37
2	OSD	raspberries and blueberries	40–60	moisture, fat, ash, protein, antioxidant activity, total phenols, and total sugar	drying reduced moisture, fat, ash, antioxidant activity, and total phenols, whereas protein and total sugar were increased in dried as compared to fresh products	51
3	OSD, shade drying, and oven drying	*Moringa oleifera* leaves	25 for shade and 60 for oven drying	moisture, fat, ash, protein, fiber, carbohydrate, vitamins, and minerals (Zn, Ca, and Fe)	the three drying methods reduced moisture, fats, and iron, whereas protein, ash, fibers, carbohydrate, vitamin, zinc, and calcium were increased as compared to fresh products	52
4	cabinet dehydration	cauliflower	70	moisture, fat, ash, protein, fiber, carbohydrate, and minerals (K, Ca, Mg, Fe, P, and Zn)	drying reduced moisture contents, however, increased protein, fiber, ash, carbohydrate, and minerals	48
5	direct solar dryer	cocoyam leaves	26.23–47.32	moisture, protein, fat, fiber, ash, and carbohydrate	drying reduced moisture and fat, however, increased carbohydrates, protein, fiber, and ash contents as compared to fresh products	47
6	air oven	tomato	70–90	moisture, protein, fat, fiber, ash, carbohydrate, and vitamin C	drying reduced moisture, protein, fats, fibers, and vitamin C, whereas it increased ash and carbohydrate contents	53
7	solar dryer integrated with TES	black pepper	47.1	moisture, protein, fats, fiber, ash, carbohydrate, and texture	drying reduced moisture contents, however, increased protein, fiber, ash, fats, carbohydrate, and texture in the dried as compared to fresh products; antioxidant activity and total phenolic content were higher in fresh black pepper as compared to the dried ones	12
8	solar dryer integrated with TES	pineapple and carrot	40–62	moisture, protein, fats, crude fiber, ash, vitamins (A and C), carbohydrate, and minerals (Ca, Mg, Na, and P)	drying reduced moisture, increased the concentration of carbohydrate, fiber, ash, minerals, and protein with a minor loss in fats	current study

most of the previous studies, an increase in concentration of carbohydrate, fats, fiber, and ash contents with minor loss in vitamin and fats when using different types solar dryers was reported. However, significant losses in nutritional composition were reported when drying on OSD. Therefore, using solar dryers integrated with TES materials significantly maintained the nutritional values of the dried products.

4. CONCLUSIONS

A solar dryer integrated with soapstone as the TES material was designed and fabricated, and its performance was evaluated by drying pineapple (*A. comosus*) and carrots (*D. carota*). The proximate analysis to determine the quality of the dried products was also carried out. The drying experiments were conducted in two modes: a dryer with and without TES materials, and the results were compared with that of OSD. During the drying process, the average initial moisture content of pineapple and carrot was reduced from 90 and 88%, respectively, to 10% wet (w.b). The drying times for pineapples in the dryer with TES, without TES, a ndOSD were 13, 24, and 52 h, respectively. However, the drying times for carrots in the dryer with TES, without TES, and OSD were 12, 23, and 50 h, respectively. This means using a dryer integrated with TES materials took less time as compared to that with OSD and when the dryer is without TES materials. It was observed that the dryer with TES materials could supply heat to the drying chamber up to 3–4 h after sunset because of the heat stored in the TES materials (soapstone). The thermal efficiency of the dryer, the collector efficiency, and storage efficiency of TES materials were calculated and found to be 45, 43, and 74.5%, respectively.

Proximate analysis was conducted for ash content, crude fiber, fat content, protein, vitamins, and minerals. It was found that all drying methods increased the concentration of carbohydrates, protein, crude fiber, ash, minerals, and vitamin A, and a greater concentration was observed using a solar dryer integrated with TES materials. However, all drying methods slightly reduced fat and vitamin C contents compared to the fresh products, and more losses were observed by using OSD, followed by solar drying without TES materials and solar drying with TES materials. Based on the performance evaluation and proximate analysis, solar dyer integrated with soapstone as a TES material can be an appropriate technology for drying agricultural products and reducing postharvest losses and improving food security, especially in rural areas. However, further studies are needed to explore the potential performance of soapstone during different weather seasons in agricultural drying application. However, further research is needed to explore the potential limitations and optimize the integration process.

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Notes

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ORIGINAL ARTICLE

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Techno-economic analysis of a solar-assisted heat pump dryer for drying agricultural products

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Abstract

Postharvest losses (PHLs) of biomaterials, such as vegetables and fruits, significantly impact food security and economic stability in developing nations. In Tanzania, PHLs are estimated to range between 30% and 40% for cereal crops and even higher for perishable crops such as fruits and vegetables. Open-sun drying (OSD) is the most extensively employed method because of its affordability and simplicity. However, OSD has several drawbacks, including difficulties in managing drying parameters, long drying times owing to adverse weather, and product contamination. The solar-assisted heat pump dryer (SAHPD) is a technology designed as an alternative solution

Nomenclature:

C_a	Annualized capital cost (USD)
C_b	Selling price of 1 kg of dried product (USD)
C_{ds}	Total cost of drying 1 kg of product (USD)
C_m	Annualized maintenance cost (USD)
C_{rf}	Running fuel cost (USD)
C_{ds}	Total cost of drying 1 kg of product (USD)
C_{re}	Cost of electricity (USD)
C_s	Cost of drying 1 kg of dried product (USD)
C_{fp}	Cost of fresh product (USD/kg)
DR	Drying Rate (kg/h)
DT	Drying Time (h)
d	Interest rate (%)
D	Number of drying days in a year (days)
D_d	Number of days used to dry one batch of the product (days)
F_c	Capital recovery factor
F_{pi}	Present worth factor
h	Specific enthalpy (kJ/kg)
i	Inflation rate (%)
n	Number of years
M_y	Weight of product dried in the dryer (kg)
M_f	Weight of fresh product (kg)
M_w	Moisture loss from the drying product (kg)
PP	Payback period (years)
P_j	Present worth of savings (USD)
Q_{Cond}	Heat delivered in condenser
RH	Relative humidity (%)
S_{kg}	Savings per kilogram of the dried product (USD)
S_j	Year-wise savings of the dried product (USD)
S_1	Savings during first year
t_d	Drying time (h)
V_s	Annualized Salvage value (USD)
W_{Comp}	Power input to the compressor (kW)
W_{fan}	Fan input power (W)

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for drying biomaterials and reducing PHL. A limited number of SAHPDs have been constructed in developing nations. Most of the works have concentrated on the performance analysis of the systems. This neglects the techno-economic assessment, which is important to provide both a quantitative and qualitative understanding of the financial viability of the technology. The present study therefore investigates the techno-economic analysis of a novel SAHPD for drying agricultural products, particularly vegetables and fruits. To determine whether the SAHPD technology is technically and economically viable, tomatoes and carrots were dried and analyzed to determine their thermal and economic performance. The results show that the initial moisture contents of tomatoes (*Lycopersicum esculentum*) and carrots (*Daucus carota*) were reduced from 93% and 88% to 10% in 11 and 12h, respectively. The coefficient of performance (COP), drying time (DT), specific moisture extraction ration (SMER) and thermal efficiency (η_T) were found to be 3.4, 2.3kg/h, 1.33kg/kWh and 54.0%, respectively. The economic analysis was assessed using the annualized cost, lifecycle savings, and payback period for the dryer's life span of 15years. The initial investment of the SAHPD was $5221.8 and the annualized cost was $1076.5. The cumulative present worth for 15years was found to be $23,828.8 and $27,553.1 for tomatoes and carrots, respectively. The payback period for tomatoes was found to be 3years, whereas for carrots it was 2.6years. Based on thermal and economic performance assessment results, the developed SAHPD is technically and economically viable to be considered for further investments.

KEYWORDS
fruits and vegetables, solar-assisted heat pump dryer, techno-economic analysis

1 | INTRODUCTION

Agriculture, an important economic sector in developing Sub-Saharan African countries, suffers from food crop postharvest losses (PHLs). PHLs of fruits and vegetables in Sub-Saharan Africa range from 30% to 80%, depending on the type of crop and location (James & Zikankuba, 2017). In Tanzania, the PHLs of food cereal crops were estimated to range between 20% and 40% in 2019 (Maziku, 2019) and more than 40% for vegetables and fruits (Dome & Prusty, 2017). According to the Ministry of Agriculture (2019), PHLs are caused by different factors such as pest infestation, poor transportation infrastructures, improper storage practices, improper harvesting and drying practices, improper weighing and packaging, a lack of reliable markets, a lack of appropriate processing technologies, and a lack of farmer's knowledge on postharvest management along the value chain. Fruits and vegetables are important agricultural products in our bodies because they provide essential nutrients such as proteins, vitamins, carbohydrates, and minerals and also significantly boost monetary exchange in local communities. However, their high perishability makes fruits and vegetables vulnerable to PHLs. The situation necessitates the development and implementation of effective yet low-cost technologies to significantly reduce food crop PHLs. According to Gunathilake et al. (2018), there are three common methods available for food preservation, namely, canning, freezing, and drying. Drying is considered the best method because it preserves agricultural products, extends shelf life, reduces volume and weight, and facilitates easy transportation, storage, and packaging of the products (Calín-Sánchez et al., 2020). Drying is one of the mitigation measures being used to reduce PHLs by lowering crop moisture content to a safe storage level.

Open-sun drying (OSD) is one of the oldest and most widely used traditional methods due to its ease of use and low cost (Sontakke & Salve, 2015; Vaghela et al., 2018). However, OSD has a number of drawbacks, such as difficulties in controlling drying kinetics (Pochont et al., 2020), long drying times (Natarajan et al., 2019), product contamination by insects, birds, and bad weather (Singh et al., 2019), loss of natural aesthetics and minerals, as well as large drying area and labor (Zachariah et al., 2021). Solar drying technologies can provide a cost-effective and efficient way to preserve food as well as reduce PHLs, particularly in developing countries.

Given current trends toward scarce and expensive conventional energy and uncertainty about their future, the combination of heat pump dryers and solar energy is becoming the most economically

TABLE 1 Specifications of heat pump components.

S/n	Name of the component	Specifications
1	Danfoss reciprocating compressor	4 HP (MTZ36GJ5EVE, LR70, low-pressure side 22.6 bar, high pressure side 29.4 bar)
2	Fan Power	175 W, 0.75 A, and 1335 rpm
3	Condenser	4 HP with a size of 1020 × 450 × 300 mm
4	Evaporator	4 HP with a size of 1020 × 510 × 400 mm
5	Expansion valve	R134a Danfoss (TEN2 R134a,068Z3348, −40/+10°C/−40/+50°F)

viable option for drying agricultural products. Solar-assisted heat pump dryers (SAHPDs) are preferred over other type of dryers due to their economical, reliable and good quality of the dried products (Şevik, 2014). The SAHPD is one of the technologies designed to overcome the limitations of passive solar dryers, which depend entirely on solar radiation, and other active drying technologies, which consume sufficient energy (Salehi, 2021). SAHPD can function successfully throughout the day, even when there is no sunlight, assuring the quality of the dried products (Gan et al., 2017). Loemba et al. (2022) conducted a comprehensive assessment of heat pumps for drying agricultural products and reported that using heat pumps significantly reduced drying time, improved specific moisture extraction, and reduced energy consumption.

The great bulk of research on the utilization of SAHPD for drying agricultural products has been on performance metrics. For example, Singh et al. (2020a) conducted a performance comparison analysis for the SAHPD and heat pump dryer (HPD) for drying banana chips. They reported that SAHPD performed better in terms of energy efficiency and specific moisture extraction ratio (SMER) compared to HPD alone due to the combination of both HPD and solar energy. In comparison with other solar drying technologies, SAHPD has been reported to reduce drying time and improve efficiency. Yahya et al. (2016) conducted a performance evaluation of the solar dryer (SD) and SAHPD for drying cassava and reported that the drying time using the SAHPD was 9 h, whereas the SD was 13 h. It was also found that the thermal efficiency and SMER for SAHPD were 30.9% and 0.47 kg/kWh, respectively, whereas for SD, the thermal efficiency and SMER were 25.6% and 0.38 kg/kWh, respectively. Yahya et al. (2018) conducted performance and economic analysis for the SAHPD fluidized bed integrated with biomass for rice drying and obtained an average SMER of 0.24 kg/kWh, with thermal dryer efficiency ranging 8.4%–25.6%. SAHPD has been reported to have a high coefficient of performance (COP), which is associated with lower operation costs for the dryer. Qiu et al. (2016) conducted a performance analysis of the SAHPD for the drying of radish, pepper, and mushrooms, and it was reported that the COP varied from 3.21 to 3.49.

Most of the studies on heat pumps have focused on the improvement of the performance of SAHPD and HPD, with few studies addressing the aspect of economic analysis on payback periods. Economic analysis is a very important aspect of the solar dryer because it provides necessary information on whether the proposed dryer is economically feasible, cost-effective, sustainable, and likely to be adopted and considered for further investment. Some of the few studies presented on economic analyses of SAHPD for drying agricultural products. Yahya et al. (2018) estimated a short payback period of 1.6 years for a solar-assisted heat pump fluidized bed dryer coupled with a biomass furnace, specifically designed for rice drying. In another study, Singh et al. (2020a) reported a payback period of 3.8 years for a SAHPD designed to dry banana chips. Qiu et al. (2016) conducted a performance and economic analysis of the heat recovery and thermal storage of a SAHPD for drying radish, pepper, and mushrooms. Their findings indicated that the cumulative net present value for radish was $10,182, whereas for pepper it was $16,072, and mushroom it was $29,749. It was also reported that the payback periods were 6, 4, and 2 years for radish, pepper, and mushroom, respectively. These various studies shed light on the economic feasibility of SAHPD in different agricultural contexts.

To the authors' knowledge, a study has yet to be conducted on the techno-economic assessment of SAHPD for drying tomatoes and carrots in the African context. Climatic conditions play a vital role in the performance of solar-assisted heat dryers. Therefore, this study aims to investigate the performance and techno-economic feasibility of a novel SAHPD for drying vegetables and fruits, specifically tomatoes and carrots, in the context of Tanzania. Tomatoes, which are botanically classified as fruits, and carrots, which are root vegetables, are essential products in Tanzania's economy as well as a source of nutrition for our health. However, they are vulnerable to post-harvest loss, especially during peak seasons.

2 | MATERIALS AND METHODS

2.1 | Materials and equipments

The SAHPD consist of heat pump components such as a condenser, evaporator, compressor, and expansion valves which are integrated with a fabricated component such as a solar collector, air duct, drying chamber, and support stand to form a complete dryer. The materials used for the fabrication of the solar dryer were bought from the local market. Some of the materials used are mild steel sheet of 1.5 mm thick, mild steel angle iron of 30 × 30 × 3 mm, clear transparent glass of 6mm thickness, insulation materials (glass wool), and bolts and nuts.

2.1.1 | The heat pump components

The heat pump components were procured from the local market and subsequently integrated with other custom-made components. Table 1 shows the specifications of heat pump components.

2.1.2 | Drying chamber

The drying chamber was constructed using 1.5mm thick mild steel sheets and reinforced with 25×25×3mm angle iron for added strength. At the top of the drying chamber, a solar collector was seamlessly integrated. To minimize heat exchange between the inside and outside of the chamber, a 25-mm-thick layer of glass wool insulation was applied. Inside the drying chamber, a black paint coating was applied to efficiently absorb solar heat energy. The design of the drying chamber allowed for the drying of 30kg of vegetables or fruits per batch.

2.1.3 | Solar collector

The solar collector was constructed using 1.5-mm-thick mild steel. On top of it, a solar collector panel measuring 946×946mm was installed to capture solar radiation. The tilt angle of the solar collector was carefully designed to ensure it received an adequate amount of solar radiation, as determined by the study conducted by Missana and Mashingo (2022). Their findings indicated an optimal tilt angle of 13.4° for efficient solar radiation capture.

2.1.4 | Air duct

A flexible air duct was employed to facilitate the flow of air between the evaporator, condenser, and drying chamber. This duct was crafted from 1.5mm thick mild steel and strengthened with 25×25×3mm angle iron. The air duct possessed an elliptical shape with a square cross section measuring 480×480mm. To minimize heat loss, it was additionally insulated with a 25-mm layer of fiberglass. Figure 2 provides a visual representation of some of the key features of the solar-assisted heat pump dryer.

2.2 | Experimental setup

A SAHPD was designed, fabricated, and tested at the Workshop of Mechanical Engineering Department, Arusha Technical College (ATC), located in Arusha Municipality, Tanzania. The compressor used in this study was a single-phase compressor manufactured by Danfoss Company, and the working fluid was R-134a. The specification of the heat pump system is shown in Table 1. Figures 1 and 2 show the schematic and photography of the SAHPD, respectively. In Figure 1, the red line shows the route of drying air in the air duct, while the blue line shows the route of the refrigerant. There are four main components in this heat pump solar drying system: a compressor, a condenser, an evaporator, and an expansion valve.

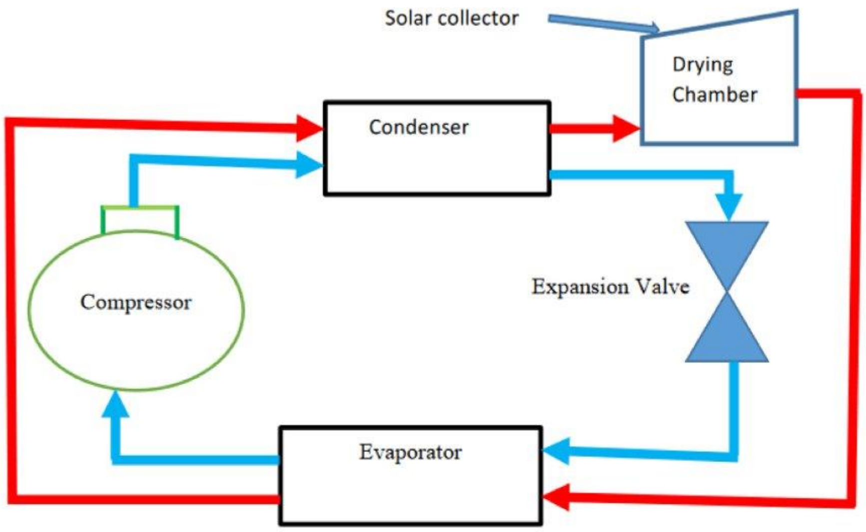


FIGURE 1 Schematic diagram of a solar-assisted heat pump drying system.

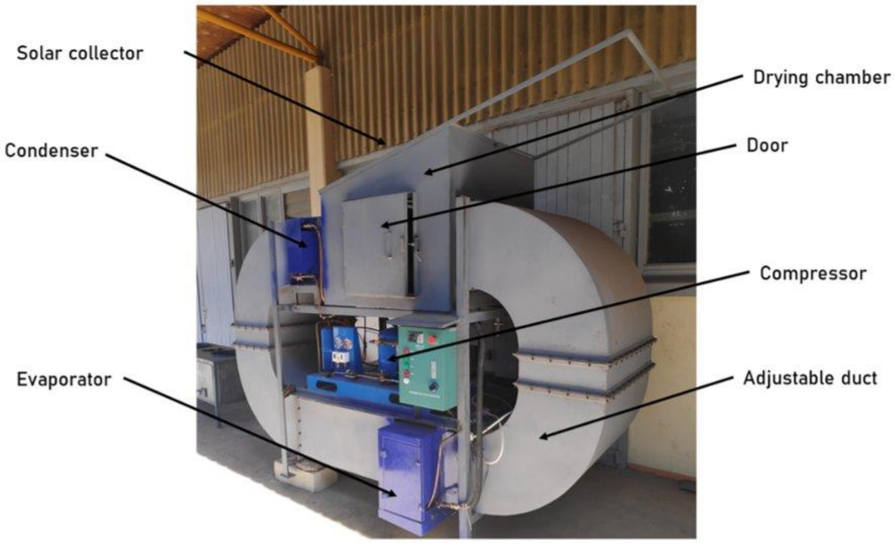


FIGURE 2 Photograph of the developed experimental setup of a solar-assisted heat pump dryer.

2.3 | Experimental procedure

The experiments were carried out on tomatoes (*Lycopersiconesculentum*) and carrots (*Daucus carota*). The samples were purchased at a local market in Arusha Region, Tanzania, washed, and sliced into about 4mm-thick pieces. According to Krishnan and Sivaraman (2017), a slice thickness of 3–4mm is considered the optimum size for drying. A sample of 30kg of tomatoes and 30kg of carrots were dried at a different time on both SAHPD and open sun. The data were recorded every 30min until the mass change of the sample became insignificant.

Three replicates were conducted for each experiment, and the average value was calculated. Several parameters were monitored throughout the experiments to assess the dryer's performance. These measurements and data collection methods were essential for evaluating the performance and efficiency of the solar-assisted heat pump dryer during the experiments.

(i) *Solar Irradiance*: Solar irradiance was measured using a TES 132 Solar power meter. A sensor probe was placed on the surface of the solar collector to capture this data.
(ii) *Weight of Drying Products*: The weight of the drying products was determined using the FF1976 Constant digital weighing scale, which was designed with a carrier on top for holding the drying products.
(iii) *Pressure*: Pressure on the high and low-pressure sides was measured using XMK pressure gauges.
(iv) *Temperature and Humidity*: Temperature and humidity inside the drying chamber were monitored using an SSN-22E USB temperature and humidity data logger meter. Three sensor probes were inserted into different positions within the drying chamber to record this data. Additionally, two similar sensor probes were located outside to measure temperature and humidity in the surrounding environment.
(v) *Compressor Parameters*: Voltage and current values of the compressor were recorded using an Agilent U1212A Clamp meter. These values were used to calculate the power consumed by the compressor and the overall power consumption of the heat pump system.

2.4 | Measuring instruments, error, and uncertainty analysis

The instruments used for measurements during experiments, the range of their measurements, accuracy, and resolution are shown in Table 2. Regardless of how precise and accurate a measurement is, it is typically subject to some degree of uncertainty. The two main contributors to these uncertainties are measurement techniques, sometimes known as random errors and measuring apparatus, commonly known as systematic errors. The total errors in measurement were calculated by using Equation (1) according to Gulcimen et al. (2016).

$$w_{th} = \sqrt{(W_1)^2 + (W_2)^2 \dots\dots\dots (W_\infty)^2} \quad (1)$$

where; W = independent variable affecting measurement.

TABLE 2 Measuring instruments and uncertainties in measurements.

S/n	Instrument	Range	Accuracy	Resolution	Error (%)	Uses
1	SSN-11E USB temperature data logger meter	−40–125°C	±0.5°C	±0.1°C	0.1414	Temperature measurement
2	SSN-22E USB temperature/humidity data logger meter	0–100% RH	±0.3 RH	±0.1 RH	0.1414	Humidity measurement
		−40–125°C	±0.3°C	±0.1°C	0.1414	Temperature measurement
3	TES 132 Solar power meter	0–2000 W/m^2	±10 W/m^2	0.1 W/m^2, 1 W/m^2	0.1414	Solar radiation measurement
4	Kestrel 3000 wind meter	0.6–40 m/s	±0.1 m/s	0.05 m/s	0.0707	Wind measurement
5	FF1976 Constant Digital weighing scale	0–40 kg	±0.14 g	0.1 g	0.1414	Weight measurement
6	Agilent U1212A Clamp meter	0–600 V	± (1.5% +3)	0.1 V	0.1414	Voltage measurement
		0–400 A	± (2.5% +3)	0.1 A	0.1414	Current measurement
7	XMK Antihunting oil gauge	1–18 MPa	±0.1	0.1 psi	0.1414	Pressure measurements

The independent variables affecting measurements were determined by using Equation (2) according to AR and Veeramanipriya (2022).

$$w_n = \sqrt{\left(W_{\text{instument}}\right)^2 + \left(W_{\text{reading}}\right)^2} \tag{2}$$

The overall errors in measurement of different parameters were given by Equation (3)

$$w_{\text{Total}} = \sqrt{\left(W_{\text{temperature}}\right)^2 + \left(W_{\text{humidity}}\right) + \left(W_{\text{solar}}\right) + \left(W_{\text{wind}}\right) + \left(W_{\text{scale}}\right) + \left(W_{\text{pressure}}\right)^2} \tag{3}$$

The combined uncertainties in the measuring devices and reading errors were determined using Equation (3) and were found to be approximately ±1.3% (rounded). This value is quite small when compared to the acceptable range of ±10% as established by Choi et al. (2018).

2.5 | SAHPD performance

SAHPD performance was evaluated by determining the moisture content (M_c), weight of water evaporated from the product (M_w), drying rate (DR), COP, and SMER.

The moisture content was determined by using the gravimetric oven drying method, in which 10 g of paste was accurately weighed in a clean, dry petridish and the weight of the sample was recorded. The petridish was then dried in an oven at 105°C for 24 h until a constant weight was obtained. Then, the petridish was placed in the desiccator for 30 min for cooling and then reweighed again. The percentage of moisture content was calculated using Equation 4.

$$M_c \text{ (On wet basis)} = \frac{\text{Total moisture content}}{\text{Total weight of product}} \tag{4}$$

The weight of water evaporated from the drying products (M_w) was calculated using Equation (5) as proposed by Fudholi et al. (2015).

$$M_w = \frac{M_o\left(M_{i-}M_f\right)}{100 - M_f} \tag{5}$$

where M_o = Initial mass of the products; M_i = Initial moisture content of the product on the wet basis; M_f = Final moisture content of the product on wet basis.

The drying rate for carrot and tomato was calculated using Equation (6) as given by Hasibuan et al. (2020)

$$\text{DR} = \frac{M_w}{t} \tag{6}$$

where M_w = Mass of water evaporated from the drying products (kg); t = Drying time (h).

SMER describes the ratio of the moisture removed (M_w) from the drying product over the total energy input to the system. It was calculated using Equation (7) as proposed by Hasibuan et al. (2020))

$$SMER = \frac{M_w}{(I_T A_{sc} + W_{comp} + W_b)t} \quad (7)$$

where M_w is the weight of water evaporated from the product (kg); I_T = Solar radiation incident to the collector; A_{sc} = Collector area (m^2); W_{comp} = Electrical energy consumed by the compressor; W_b = Electrical energy consumed by the fans.

The COP is the ratio of usable heat or heat energy released by the refrigerant in the condenser to the electrical energy required by the compressor. It was calculated using Equation (8) as proposed by (Singh et al., 2020b).

$$COP_{HP} = \frac{h_2 - h_3}{h_2 - h_1} \quad (8)$$

h_2 = Enthalpy (kJ/kg) of the superheated vapor from the compressor; h_1 = Enthalpy (kJ/kg) of the saturated vapor state from the evaporator; h_3 = Enthalpy (kJ/kg) of the saturated liquid state from the condenser.

The pressure (kPa) and temperature (°C) for refrigerant for sanction (low) and sanction side (high) was obtained from the pressure gauges, whereas enthalpies in (kJ/kg) were obtained from the refrigerant R134a thermodynamic table and pressure-enthalpy chart.

Figure 3 illustrates the path of the refrigerant and its various states as it undergoes transitions between liquid, liquid-to-vapor, and vapor phases within the system. At the initial point of entry, denoted as "Point 1," into the compressor, the refrigerant is observed to be in a supersaturated vapor condition. Within the compressor, its pressure undergoes a significant increase, evident in the pressure-enthalpy diagram as it moves from "P1" to "P2." As it exits the compressor at "Point 2," the refrigerant is in a superheated vapor state. Subsequently, the refrigerant proceeds from "Point 2" to "Point 3," where it releases heat into the drying chamber and leaves the condenser in a fully saturated liquid state, completing this phase of the cycle. The high-pressure liquid then enters the expansion chamber, where it experiences a pressure drop from "P2" to "P1" due to the expansion process. Upon exiting the expansion valve at "Point 4," the refrigerant exists in a two-phase state, comprising a mixture of liquid and vapor. It then enters the evaporator, where it absorbs heat from the surrounding environment. During this stage, all the liquid transforms into a supersaturated vapor state, continuing the cycle. This intricate process of phase changes and heat exchange within the system is integral to facilitating the drying process efficiently.

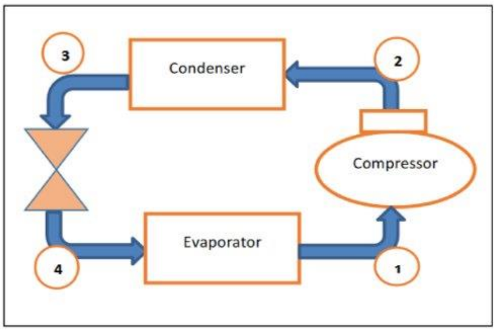
The thermal efficiency of the drying system was determined by using Equation 9, according to Hasibuan et al. (2020).

$$\eta_T = \frac{M_w H_{fg}}{I_T A_{sc} + W_{comp} + W_f} \quad (9)$$

where M_w = Weight of water evaporated from product (kg); I_T = Solar radiation incident to the collector (W/m^2); A_{sc} = Collector area (m^2); H_{fg} = Latent heat of vaporization was obtained from a table of saturation properties for steam temperature at an average drying temperature; W_{comp} = Electrical energy consumed by the compressor; W_f = Electrical energy consumed by fan.

2.6 | SAHPD economic analysis

The economic analysis of the SAHPD was evaluated using three economic standard methods, namely, annualized cost, life cycle savings, and payback period. Some assumptions about the parameters were made for the evaluation of the economic analysis of the dryer; some were based on the Tanzanian economic scenario, and others on previous studies. These includes the fact that the life span of a solar dryer was assumed to be 15 years. Inflation rates of 4.8% were adopted from the monthly economic review report from the Bank of Tanzania (2023). Further, the 7% annual interest rate stated by Aly et al. (2019) was adopted. Since the SAHPD requires minimal service, the maintenance cost and salvage value were considered to be 5% of the annualized capital cost, as utilized in the study by Philip et al. (2022). Table 3 shows a summary of the important parameters used during the analysis.



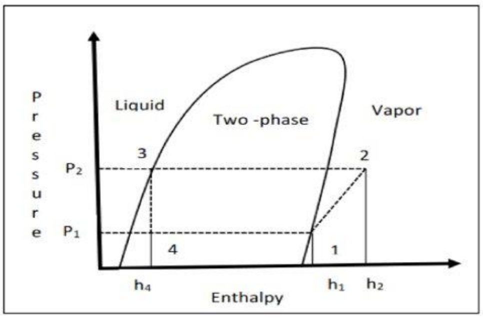


FIGURE 3 Schematic and pressure-enthalpy diagram.

TABLE 3 Summary of parameters for economic analysis of the solar-assisted heat pump dryer (SAHPD).

S/n	Parameters	Value
1	Capital investment cost	$5221.8
2	Maintenance cost	5% of annual capital cost
3	Salvage value	5% of annual capital cost
4	Inflation rate (i)	4.8%
5	Dryer life span (n)	15 years
6	Cost of fresh tomatoes	$0.15/kg
7	Selling price of the dried tomatoes	$4/kg
8	Cost of fresh carrots	$0.2/kg
9	Selling price of the dried carrots	$3/kg
10	Interest rate (d)	7%
11	Number of days of operation per year (D)	300 days
12	Dryer drying capacity	30 kg/batch/day
13	Cost for electricity	0.155 $/kWh

2.6.1 | Annualized cost

The annualized cost method estimates the cost of drying products on an annual basis. The annualized cost was calculated according to Philip et al. (2022) by using Equation 10.

$$C_a = C_{ac} + C_m - V_s + C_{rf} + C_{re} \quad (10)$$

where C_a=Annualized cost of the dryer (USD); C_{ac}=Annualized capital cost (USD); C_m=Annualized maintenance cost (USD); V_s=Annualized salvage value (USD); C_{rf}=Running fuel cost (USD); C_{re}=Cost of electricity (USD).

$$C_{ac} = C_{cc}F_c \quad (11)$$

where C_{cc}=Capital investment cost of the dryer (USD); F_c=Capital recovery factor.

$$V_s = VF_s \quad (12)$$

where V=Salvage value (USD); F_s=Salvage fund factor.

$$F_c = \frac{d\,(1+d)^{\,n}}{(1+d)^n - 1} \quad (13)$$

$$F_s = \frac{d}{(1+d)^n - 1} \quad (14)$$

where d=Interest rate; n=Lifespan of solar dryer.

Weight (kg) of the dried product in the dryer is given by Equation 15 according to Philip et al. (2022).

$$M_y = \frac{DM_d}{D_b} \quad (15)$$

where D=Number of drying days in a year; M_d=Weight (kg) of dried product removed from the dryer per batch; D_b=Number of days for drying one batch of the product.

The cost for drying 1 kg of the dried products (C_s) is given by Equation 16 according to Philip et al. (2022).

$$C_s = \frac{C_a}{M_y} \quad (16)$$

The running fuel cost (C_{rf}) for this particular dryer is assumed to be zero because the source of energy to power the compressor of the heat pump is electricity. The running cost of electricity was calculated using Equation (17) according to Philip et al. (2022).

$$C_{re} = R \times W \times C_e \quad (17)$$

where C_e=Unit charge of electricity; R=Number of hours of running a heat pump in a year; W=Power supplied to the system.

2.6.2 | The life cycle savings

The method describes how much can be saved on a drying basis and then projects the present value of annual savings over the dryer's lifespan (Philip et al., 2022). The cost of fresh product per kilogram of dried product was calculated using Equation 18, according to Chavan and Thorat (2021).

$$C_{dp} = C_{fp} \times \frac{M_f}{M_d} \quad (18)$$

where C_{fp}=Cost of fresh product (USD/kg); M_f=Weight of fresh product (kg).

The total cost of drying 1 kg of the product (C_{ds})is given by the sum of the total cost of fresh product (C_{dp}), and the cost required to dry 1 kg of the product (C_s) was calculated using Equation 19 according to Chavan and Thorat (2021).

$$C_{ds} = C_{dp} + C_s \quad (19)$$

Considering the dried products by dryer for this particular project are to be branded, the savings per kilogram of the dried product (S_{kg})in annual basis are expressed in Equation 20, according to Prakash et al. (2017).

$$S_{kg} = C_b - C_{ds} \tag{20}$$

where C_{ds} = Total cost of fresh product; C_b = Selling price of 1 kg of dried product (USD).

Batch-wise savings (S_b) on drying days are expressed in Equation 21, according to Prakash et al. (2017).

$$S_b = S_{kg} \times M_d \tag{21}$$

S_{kg} = The savings per kilogram of dried products on an annual basis.

Daily-wise savings (S_d) on drying days is expressed in Equation 22, according to Prakash et al. (2017).

$$S_d = \frac{S_b}{D_h} \tag{22}$$

D_b = Number of days for drying one batch of the product.

2.6.3 | Annual saving's present worth

Year-wise savings of the drying products (S_j) under study in the nth year are expressed in Equation 23 as proposed in Prakash et al. (2017).

$$S_n = S_d \times D \times (1+i)^{n-1} \tag{23}$$

where I = Inflation rate (%); $F_{pn} \times S_n D$ = Number of drying days in a year; S_d = Savings per day (USD).

The present worth of savings in the nth year is given by Equation 24, according to Prakash et al. (2017).

$$P_n = F_{pn} \times S_n \tag{24}$$

where F_{pn} = Present worth factor for the nth year (USD); S_n = Yearly savings for drying product in nth year (USD).

The present worth factor for the nth year is given by Equation 25, according to Prakash et al. (2017).

$$F_{pn} = \frac{d}{(1+d)^n} \tag{25}$$

where d = Interest rate and n = number of years.

Life cycle savings is found by summation of yearly savings of present worth over life span of the dryer.

2.6.4 | Payback period (PP)

The payback period (PP) was calculated by using Equation (26) according to Prakash et al. (2017).

$$PP = \frac{\ln\left(1 - \frac{C_{cc}}{S_1}(d-i)\right)}{\ln\left(\frac{1+i}{1+d}\right)} \tag{26}$$

where d = Annual interest rate = 7%; i = Inflation rate = 4.8%; S_1 = Savings during the first year; C_{cc} = Capital investment cost of the dryer (USD).

3 | RESULTS AND DISCUSSION

3.1 | Performance evaluation

The experiments were carried out between May and November 2022, from 8:00 a.m. to 8:00 p.m. This is the period when there is a sufficient amount of sun radiation in the Arusha Region. The solar radiation ranged from 90 W/m^2 to 1060, and the minimum irradiation was observed during the morning and evening, whereas the maximum irradiation was observed around noon. Figure 4 depicts the time-dependent fluctuations in mean hourly solar irradiance (W/m^2) during drying experiments. The minimum irradiations were observed during the morning and evening, whereas the maximum irradiations were observed around 12.30 p.m.

Figure 5 shows the relationship between the average temperature inside the drying chamber, ambient temperature, and solar radiation. The startup of the system was done at 8:00 a.m., and the heat pump was set to a temperature of 50°C and an average air velocity of 1.5 meters per second because drying products using these parameters maintains vital components such as protein, vitamins, and minerals, as reported by Das Purkayastha et al. (2013) for tomatoes and Gojiya and Vyas (2015) for Kothimda product. In addition, a temperature range of 45–60°C is safe for drying heat-sensitive products such as fruits and vegetables and ensuring the quality of the dried products (Sontakke & Salve, 2015). The temperature inside the drying chamber gradually started to increase until it reached a maximum average of 65°C around 12:30 p.m. during the time of peak solar irradiance. The sliding gate with fiber wood that was installed on the top of the solar collector was designed to restrict the development of excess temperature in the drying chamber and was closed when the temperature rose above 65°C. When the solar radiation was not available, the maximum temperature attained by the heat pump alone was 51°C. In this case, the heat energy from the solar collector was contributing to a rise in temperature of about 14°C, which is about 21.5% of the total maximum temperature recorded in the drying chamber. However, the temperature inside the drying chamber was in the range of 45–65°C, depending on the intensity of solar radiation. This result is in agreement with Yahya (2016), who used SAHPD integrated with a biomass furnace for drying red chilli. In that study, it was found that the solar collector's contribution to heat energy ranged from 2.7% to 30%, while the condenser's contribution ranged from roughly 43.7% to 50.4%. The current study also agrees with Yahya et al. (2016), who contrasted solar dryer and SAHPD for drying cassava and reported that the average contribution of energy from solar collector was 44.6%. Based on these observations, solar collector plays important role of supplying additional energy to the system for drying.

The humidity in the drying chamber and the ambient relative humidity are shown in Figure 6. The ambient relative humidity varies from 25.2 to 65.5%, whereas the relative humidity inside the drying chamber varies from 15.3 to 65%. The relative humidity in the drying chamber was lower than ambient humidity because the evaporator acts as a dehumidifier, reducing humidity in the drying chamber. In

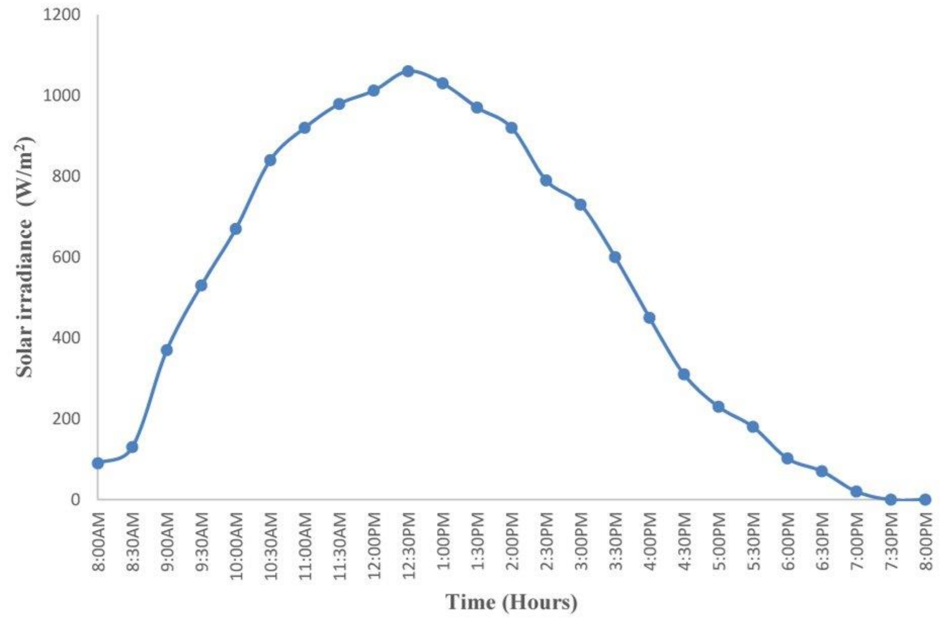


FIGURE 4 Variation of solar radiation with time.

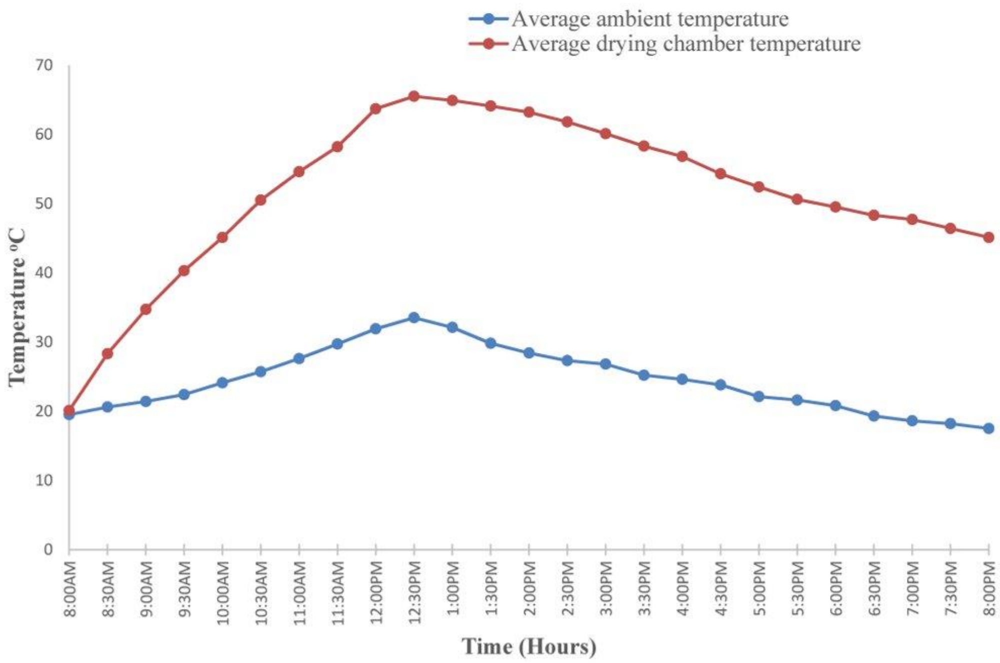


FIGURE 5 Variation of ambient and temperature in the drying chamber.

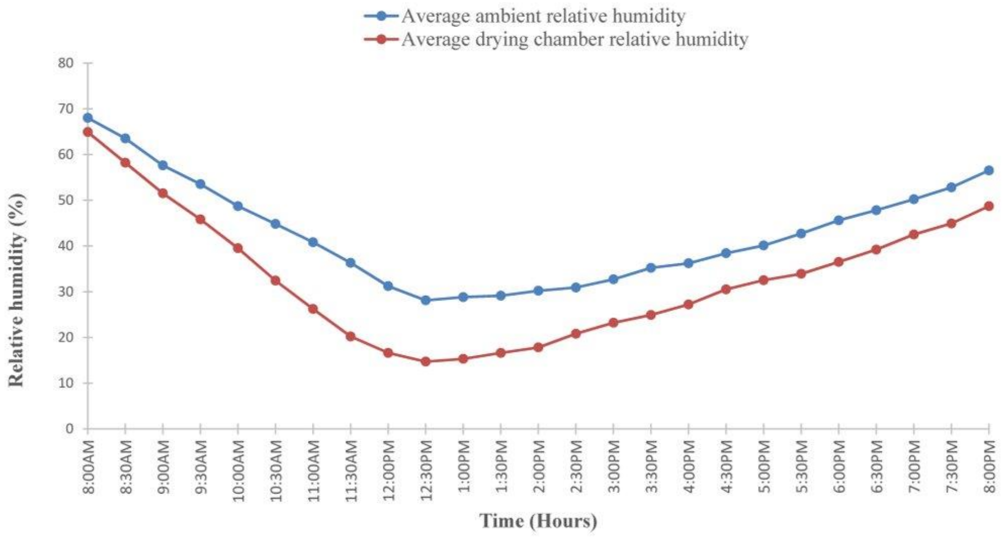


FIGURE 6 Variation of ambient relative humidity in the drying chamber.

this particular study, it was observed that relative humidity inside the drying chamber was significantly low during a day when solar radiation was at its maximum and gradually increased after sunset. This study's findings are in agreement with those of Yahya (2016), who used a solar-assisted heat pump integrated with a biomass furnace for chilli drying. In that particular study, it was reported that the humidity in the drying chamber was lower compared with the ambient humidity, with a difference of about 47.3%. Therefore, evaporators and solar collectors play an important role in controlling relative humidity during drying.

3.1.1 | Drying kinetics

The percentage of moisture reduction for carrots and tomatoes in SAHPD and OSD is shown in Figure 7. The initial moisture content for tomatoes and carrots decreased from 93% and 88% to 10% in 12 and 11 h, respectively. The drying rate in the SAHPD dryer was higher at the initial stage and continuously declined with time; a similar situation happened on the OSD, in which the rate of moisture reduction was higher on the first day and relatively slow in the following days. The higher drying rate at the initial stage is caused by the loss of water from the surface of the slices of the drying products, which enables quick water flow and evaporation. The initial moisture contents of the second and third days of the tomatoes dried in the open sun were slightly higher as compared to the final moisture contents obtained on the second and third days because of the hygroscopic behavior of tomatoes, in which they tend to absorb water during the night when humidity increases. The hygroscopic behavior was also reported by Das Purkayastha et al. (2013) for drying tomato slices and Owureku-Asare et al. (2022) during the quality assessment of solar-dried tomato slices. It was reported that dried products increased in water contents during the following drying days, which was caused by the absorption of water from high-humidity air.

Figure 8 shows the variation of weight reduction with time for tomatoes and carrots using SAHPD and OSD. The fresh sample of 30 kg was dried in the SAHPD at different times, and the final weight of the dried products was 3.3 and 4 kg for tomatoes and carrots, respectively. The time taken to reduce the fresh weight to the final weight was 12 h for tomatoes and 11 h for carrots. The drying time using SAHPD is shorter compared to the 42 h used in OSD to dry tomatoes and carrots. The drying time of 12 h for tomatoes in this study is in agreement with the results obtained by Coşkun et al. (2017), who dried tomato slices using a closed-loop heat pump dryer in Table 4A. In that particular study, the tomato slices were dried at three different temperatures (35, 40, and 45°C), and the time taken to dry tomatoes to a final moisture content less than 10% was 12, 10, and 7 h, respectively. However, the drying time of 12 h for tomatoes from this work differs from the results obtained by Karabacak and Atalay (2010) in Table 4A. It was reported that tomatoes dried in 78 h in HPD and 148 h in OSD. This is because the tomatoes were sliced quarterly, whereas in this particular study, the tomatoes were sliced into 4-mm thickness. According to Sadin et al. (2014), drying rate increases with a reduction in product thickness. In comparison with carrots drying. The results in this study are slightly different from those of Aktaş et al. (2017) in Table 4A, who used HPD and an infrared-heat pump dryer for carrot drying. It was reported that the moisture content of carrots was reduced from 7.06 g water/g dry to 0.14 g water/dry matter in 6.8 h at 40°C and 5.8 h at 50°C. The difference

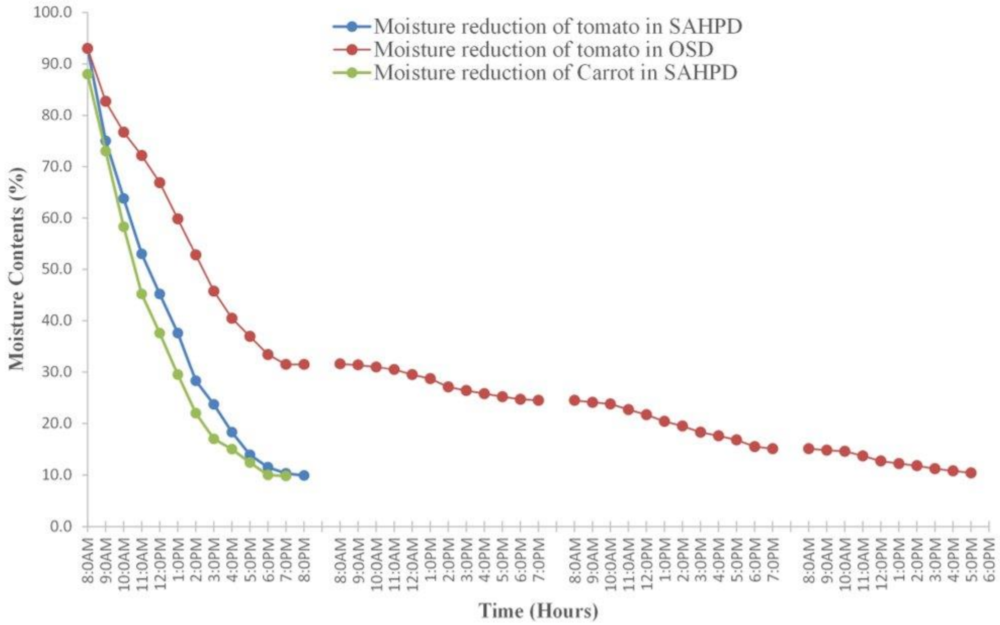


FIGURE 7 Moisture reduction of tomato and carrot in the solar-assisted heat pump dryer (SAHPD) and open-sun drying (OSD).

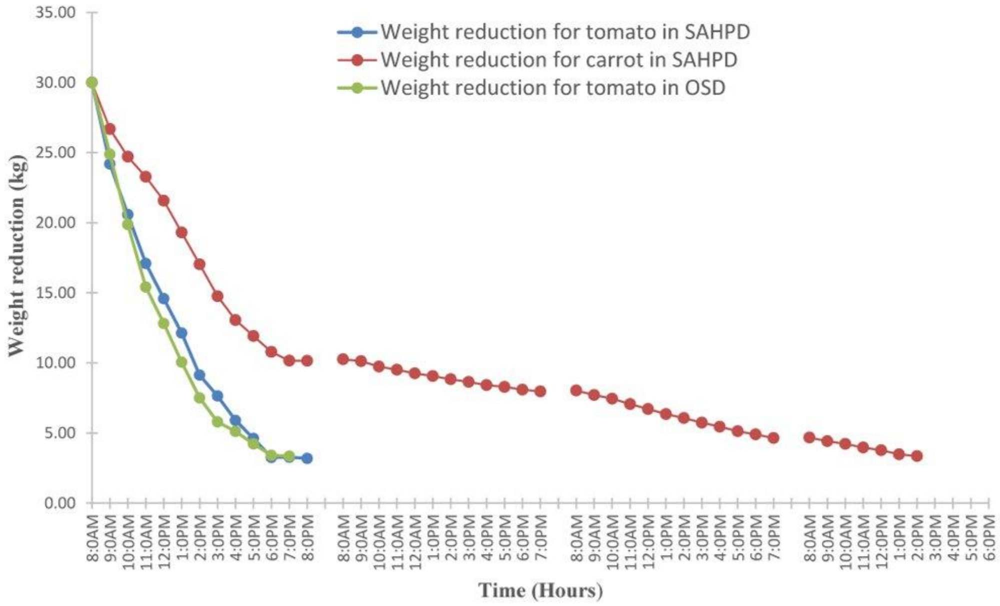


FIGURE 8 Weight reduction of tomato and carrot in the solar-assisted heat pump dryer (SAHPD) and open-sun drying (OSD).

TABLE 4A Selected studies on the performance of solar-assisted heat pump dryer (SAHPD) and open-sun drying (OSD) for drying tomatoes and carrots.

				Drying time (h)		Drying temp (°C)					
S/N	Dyer type	Product dried	Load (kg)	Dryer	OSD	Dryer	OSD	SMER (kg/kWh)	COP	Thermal efficiency (η)	References
1	HPD	Tomatoes	20	78	148	–	–	1.573	–	–	Karabacak and Atalay (2010)
2	Vacuum assisted solar dryer	Tomatoes	5	6	7.5	48	30	–	–	–	Rajkumar et al. (2007)
3	HPD	Carrots	–	6.8 and 5.8		45 and 50	–	–	2.96	–	Aktaş et al. (2017)
4	HPD	Tomatoes	2.1	12,10,7	–	35,40,45	–	0.324	2.71	–	Coşkun et al. (2017)
5	SAHPD	Tomatoes and carrots	30	12 and 11	42	45–65	20–30	0.82	3.4	54.0	Current work

TABLE 4B Selected studies on the performance of solar-assisted heat pump dryer (SAHPD) and open-sun drying (OSD) for drying other vegetables and fruits.

				Drying time (h)		Drying temp (°C)					
S/N	Dyer type	Product dried	Load (kg)	Dryer	OSD	Dryer	OSD	SMER (kg/kWh)	COP	Thermal efficiency (η)	References
1	SAHPD	Mangoes	80	16.3	–	–	–	2.05	3.69	33.4	Wang et al. (2019)
2	SAHPD	Red Chili	22	11	62	70.5		0.14	3.84	9.03	Yahya (2016)
3	SAHPD	Rice	11	0.3	–	61.4–80.9	–	3	3.7	15.4	Yahya et al. (2018)
4	SAHPD	Banana chips	13.5	4	–	48.15	–	1.417	3.43	56.69	Singh et al. (2020b)
5	SAHPD	Chili peppers	10	24		53		2.37	3.17	31.2	Naemsai et al. (2019)
6	SAHPD	Grain	3760	42	–	26.4–41.8	–	1.934	5.03	40.27	Gu et al. (2022)
7	SAHPD	Curcuma	30.7	8	–	57.7	–	2.07	4.35	34.3	Hasibuan et al. (2020)
8	SAHPD	Pineapples	0.6	5	–	37, 40, 43	–	0.218, 0.23, 0.26	2.9, 3.1 and 3.25	–	Salehi (2021)
9	HPD	Mushroom	90	11	–	55	–	2.3	–	–	Juan et al. (2013)
10	SAHPD	Cassava	30.8	9	–	45	–	0.38	3.38	30.9	Yahya et al. (2016)
11	SAHPD	Banana		21		48–52	–	0.6	2.72	–	Kuan et al. (2019)

could be due to less quantity of the annually dried products in the dryer, in which it was reported 45.99 kg compared to 1,200 kg of dried carrots, hence making less annual savings.

The weight of water evaporated during the drying of 30 kg of tomatoes and carrots was calculated using Equation (5) and found to be 26.7 kg for tomatoes and 26 kg for carrots. The drying rate was calculated from Equation (6) and found to be 2.2 and 2.3 kg/h for tomatoes and carrots, respectively. The SMER was calculated from Equation 7 and found to be 1.29 kg/kWh for tomatoes and 1.33 kg/kWh for carrots. The SMER of 1.33 kg/kWh in this study is within the range of 0.156–9.25 kg/kWh reported by Loemba et al. (2022) for most of the heat pump dryers. The COP was calculated from Equation 8 and found to be 3.4, and the thermal efficiency was calculated from Equation 9 and found to be 54.0%. The COP obtained from this study is within the range reported by Loemba et al. (2022) during the compressive assessment of heat pumps for agricultural products, in which it was reported that most of the heat pumps have COPs ranging from 1.94 to 5.38. The thermal efficiency of SAHPD obtained in this study is in agreement with the 56.69% reported by Singh et al. (2020b) in Table 4B during the application of SAHPD for the drying of banana chips.

Table 4A shows some selected studies on the performance of HPD and drying on OSD for tomatoes and carrots. It can be seen from the table that most of the studies have focused on the application of heat pumps alone to the drying of carrots or tomatoes and not a combination of heat pumps and solar energy. Table 4B shows a few selected studies on the performance of SAHPD and OSD for drying other vegetables and fruits using SAHPD. It can be seen from the table that most of the studies have concentrated on the performance of SAHPD using other agricultural products, particularly bananas, and not tomatoes and carrots. From the table, the SMER of the selected studies ranges for SAHPD ranges from 0.6 to 3 kg/kWh, and the COP ranges from 2.72 to 5.03 and thermal efficiency from 9.03 to 56.99. These results are in agreements with the results of the current research under study.

3.2 | Economic analysis of the SAHPD

The entire initial capital investment, which includes the cost of materials for SAHPD fabrication, was first established, and the total cost was approximately $5222.8, as shown in Table 5. The capital cost was used to calculate the annualized cost and other subsequent economic parameters.

3.2.1 | Annualized cost method

According to Bishoge et al. (2018), Tanzania has potential global horizontal radiation of 4–7 kWh/m^2/day and sunshine hours ranging from 2800 to 3500 h. However, SAHPD can work even when the sun radiation is not available. For this particular study, the dryer operating time was assumed to be 300 days a year, and the rest of the days were for maintenance of the dryer. Thirty kilograms of fresh tomatoes and thirty kilograms of fresh carrots were loaded in the dryer in consecutive days, and the weight of dried product removed from the dryer per batch was 2.4 and 4 kg for tomatoes and carrots, respectively. The annual weight of dried product was calculated according to Equation (21) and found to be 720 kg for tomatoes and 1200 kg for carrots. The annual capital cost was calculated from Equation (11) and was found to be $569.2. The annualized cost was calculated using Equation (10) and found to be $1076.5. The cost for drying 1 kg of tomatoes and carrots was calculated using Equation (16) and found to be $1.5 and $0.9 for tomato and carrot, respectively.

3.2.2 | The life-cycle savings

This method calculates the daily savings of the SAHPD and then projects the present worth of annual savings for a pre-determined dyer lifespan. The cost of fresh product per kilogram of dried product was calculated using Equation (18) and found to be $1.8/kg for tomatoes and $1.5/kg for carrots. The total cost of drying 1 kg of

TABLE 5 Capital investment of solar-assisted heat pump dryer (SAHPD).

S/N	Item description	Unit	Quantity	Unit cost ($)	Amount ($)
1	Procurement of heat pump (compressor, condenser and evaporator)	pcs	1	3913.0	3913.0
2	Solar collector glass 6 mm thickness	pcs	1	130.4	130.4
3	Mild steel sheet (2440 × 1220 × 1.5 mm)	pcs	10	56.5	565.2
4	Rubber gasket	roller	1	43.5	43.5
5	Angle iron (30 × 30 × 3 mm)	pcs	6	13.0	78.0
6	Bolts and nuts	kg	3	4.3	13.0
7	Black paint	Liters	4	1.3	5.2
8	Red oxide primer	Liters	10	1.3	13.0
9	Silver paint	Liters	20	1.3	26.1
10	Electrical and electronic control panel	pcs	1	434.8	434.8
	Total cost ($)				5221.8

TABLE 6 Summary of annul savings, NPW, and cumulative for drying tomatoes and carrots.

Tomatoes				Carrots		
Year	Annual savings ($)	Net present worth ($)	Cumulative present worth ($)	Annual savings ($)	Net present worth ($)	Cumulative present worth ($)
1	1957.7	1829.6	1829.6	2263.7	2115.6	2115.6
2	2051.7	1792.1	3621.7	2372.4	2072.2	4187.81
3	2150.3	1755.3	5377.0	2486.4	2029.6	6217.42
4	2253.5	1719.2	7096.2	2605.8	1987.9	8205.34
5	2361.7	1683.9	8780.0	2730.9	1947.1	10,152.41
6	2475.2	1649.3	10,429.3	2862.0	1907.1	12,059.49
7	2594.0	1615.4	12,044.8	2999.4	1867.9	13,927.39
8	2718.6	1582.2	13,627.0	3143.5	1829.5	15,756.90
9	2849.1	1549.7	15,176.7	3294.4	1791.9	17,548.83
10	2985.9	1517.9	16,694.6	3452.6	1755.1	19,303.94
11	3129.3	1486.7	18,181.3	3618.3	1719.0	21,022.99
12	3279.5	1456.2	19,637.4	3792.1	1683.7	22,706.71
13	3437.0	1426.2	21,063.7	3974.1	1649.1	24,355.83
14	3602.0	1396.9	22,460.6	4164.9	1615.2	25,971.07
15	3775.0	1368.2	23,828.8	4364.9	1582.0	27,553.11

TABLE 7 Some of the previous studies on the economic analysis of different SAHP drying technologies.

S/n	Type of solar dyer	Type of dried product	Weight of the product (kg)	Initial investment cost ($)	Life span	Method used	Findings	Reference
1	SAHPD	Banana chips	13.5	928.52	–	Total annual gain, Return period of investment and payback period	Payback period 3 years. Yearly profit was $95	Singh et al. (2020b)
2	SAHPD with waste Heat Recovery	Carrots	0.731	–	20	Life circle method and payback period	Cumulative present worth of $1988 and payback period of 5 years	Xie et al. (2021)
3	SAHP fluidized bed dryer	Rice	10	2550	10	Net present value an Payback period	Net present value was $8563 an Payback period 1.6	Yahya et al. (2018)
4	Heat recovery and thermal storage solar-assisted heat pump dryer	Radishes Peppers Mushroom	10 10 10	3423	20	Life cycle method and payback period	Cumulative net present value for radish was $10,182, for pepper was $16,072 and mushroom was, $29,749. Payback for radish was 6 years, Pepper 4 years and mushroom 2 years	Qiu et al. (2016)
5	SAHPD	Tomatoes and carrots	30	5222.6	15	Annualized cost Life cycle savings and Payback period	Annualized cost found $1076.5. Cumulative present worth $23,828.8 for tomatoes and $27,553.11 for carrots. Payback period 3 years for tomatoes and 2.6 years for carrots	This study

the product was computed using Equation (19) and found to be $3.4/kg for tomatoes and $2.4/kg for carrots, respectively. Daily savings (batch-wise savings) for drying were calculated using Equation (22) and found to be $9.6 tomatoes and $12 for carrots.

The summary of annual savings, Net present worth, and cumulative present worth for tomatoes and carrots for 15 years is depicted in Table 6. The annual savings are $3775 for tomatoes and $4364.9 for carrots. The cumulative present worth is $23,828.8 for tomatoes and $27,553.11 for carrots. Therefore, with the initial investment of $5221.8 for SAHPD, savings of $23,828.8 and $27,553.11 can be obtained over a period of 15 years for tomatoes and carrots, respectively. This result is in agreement with the results reported by Qiu et al. (2016) for drying radish, pepper, and mushrooms using heat recovery and thermal storage in a SAHPD for a lifespan of 20 years. In that particular study, the cumulative net present value for radish, pepper, and mushroom was $10,182, $16,072, and $29,749, respectively. According to Cui et al. (2022), a higher present cumulative value indicates a better project.

3.2.3 | Payback period

The payback period was calculated from Equation (26) and found to be 3 years and 2.6 years for tomatoes and carrots, respectively. This means it takes 3 years to recover the initial investment of $5221.8 from the SAHPD for tomatoes and 2.6 years for carrots. The difference between the two is caused by the higher amount of moisture content in the tomatoes (93%), as compared to the carrots (88%). When tomatoes are dried, they remain with less dried matter 2.4 kg whereas carrots remain with 4 kg of dried matter. In this case, carrots have slightly higher annual savings than tomatoes. Hence, drying carrots by using SAHPD could be more profitable as compared to tomatoes. The obtained payback periods are in the range of 1.6–3.6 years for most of the SAHPD, as reported by Loemba et al. (2022) when conducting a comprehensive assessment of heat pump dryers for agricultural products. The payback period in this study is less as compared to the 5 years reported by Xie et al. (2021) for SAHPD with waste heat recovery. The difference could be due to less quantity of the annually dried products in the dryer, in which it was reported 45.99 kg compared to 1,200 kg of dried carrots, hence making less annual savings. Since the dryer is designed for drying vegetables and fruits, the results can also be compared by Qiu et al. (2016) for drying radishes, peppers, and mushrooms using a heat recovery and thermal SAHPD. In that particular study, 10 kg of each radish, pepper, and mushroom were collected by using a heat recovery and thermal storage SAHPD, and the payback periods for radish, pepper, and mushroom were 6 years, 4 years, and 2 years. Since the payback obtained in this study for both tomatoes and carrots is less compared to the investment period of 15 years of the solar dyer's lifespan, this project is attractive for investment.

Table 7 shows a summary of selected studies on the economic analysis of different SAHP drying technologies; however, the annualized cost method is not used in the study because there are limited studies using this method for SAHPD. It can be noted that most studies on economic analysis have concentrated on the assessment of payback periods, with very few focusing on other economic parameters such as annualized costs and life cycle savings.

4 | CONCLUSION

A prototype of SAHPD was designed, fabricated, and tested for drying agricultural products. A techno-economic analysis was conducted for drying tomatoes and carrots. The performance analysis of the SAHPD was analyzed using COP, DT, SMER, and thermal efficiency, and the results were found to be 3.4, 2.3 kg/h, 1.33 kg/kWh, and 54%, respectively. The time taken to dry carrots and tomatoes to their final moisture content was 11 and 12 h, respectively, whereas the time taken to dry tomatoes in OSD was 42 h. The performance analysis revealed that the use of SAHPD in the drying of vegetables and fruits reduces drying time and energy consumption. The economic analysis was analyzed by using the annualized cost, lifecycle savings, and payback period for a life span of 15 years, which was considered the maximum time of dryer operation before disposal. The initial investment in the SAHPD was $5221.8. The annualized cost was found to be $1076.5. The cumulative present worth for 15 years was found to be $23,828.8 and $27,553.1 for tomatoes and carrots, respectively. This is a good savings based on the initial investment in the dryer. The payback periods for tomatoes (3 years) and carrots (2.6 years) were in good agreement with previous works. The use of SAHPD in the drying of carrots produces more return as compared to tomatoes. This study has therefore revealed that the SAHPD is economically feasible and is recommended for further investments in order to reduce postharvest loss, particularly in vegetables and fruits, in developing countries. More research is needed, however, to investigate the use of SAHPD for the drying of high-volume commercial crops such as tobacco and tea. These crops have traditionally consumed large amounts of biomass materials, such as firewood, for curing, which leads to deforestation.

AUTHOR CONTRIBUTIONS

Evordius Laurent Rulazi: Conceptualization (equal); data curation (lead); formal analysis (lead); funding acquisition (supporting); investigation (equal); methodology (equal); project administration (supporting); resources (supporting); software (equal); supervision (supporting); validation (lead); visualization (lead); writing – original draft (lead); writing – review and editing (supporting). **Baraka Kichonge:** Conceptualization (equal); data curation (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (equal); methodology (equal); project administration (equal); resources (supporting); software (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (supporting); writing – review and editing (supporting). **Janeth Marwa:** Conceptualization (supporting); data curation (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (supporting); methodology (equal); resources (equal); software

(equal); supervision (equal); validation (equal); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Thomas T. Kivevele:** Conceptualization (lead); data curation (equal); formal analysis (equal); funding acquisition (lead); investigation (equal); methodology (equal); project administration (lead); resources (lead); software (equal); supervision (lead); validation (equal); visualization (equal); writing – original draft (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this research study are available upon request.

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CERTIFICATE OF GRANT OF PATENT

Regulations 29(3)

In accordance with Sections 28(1) of the Patents (Registration) Act, Cap. 217 R.E. 2002, it is hereby certified that a Patent having the number TZ/P/2023/00088 has been granted to:

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In respect of an invention described in an application for that Patent Certificate having a

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