DESIGN, CONSTRUCTION AND COMPARATIVE THERMAL ANALYSIS OF SOLAR DRYERS FOR DRYING CASSAVA USING DIRECT SUN DRYING, INDIRECT AND GREENHOUSE METHODS

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2024/2025 SESSION

CERTIFICATION

This is to certify that this project work has been written by **MUFUTAU SAHEEDAT YETUNDE** with matric number **HND/23/SLT/FT/0471** and has been read and approved as meeting the parts of the requirements for the award of Higher National Diploma (HND) in Science Laboratory technology Department (Physics and Electronics Unit), Institute of Applied Sciences, Kwara State Polytechnic.

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DEDICATION

This work is dedicated to Almighty God, for his grace, mercy and guidance over us before, during and after the completion of my academic pursuit. All Glory to God and my Supervisor (**Dr. Olaore K.O.**) also to my parent, and friends who has never failed to give me financial and moral support for all my needs during the time i developed my systems and for teaching me that even the largest task can be accomplished if it is done one step as a time.

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Futhermore, my special thanks goes to the Head of Department of Science Laboratory Technology **Dr. Usman A.** and our Head of Physics and Electronics Unit **Mr. Salahu Bashir** for been there for me all in time.

May God bless and keep you all (amen).

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ABSTRACT

This study presents the development and evaluation of innovative solar drying systems designed to utilize solar energy for the effective drying of agricultural products, particularly cassava (Manihot esculenta Crantz), thereby minimizing post-harvest losses in Nigeria. Traditional sun drying techniques face significant challenges, including direct exposure to varying weather conditions, susceptibility to pests and rodents, inadequate monitoring facilities, and the prohibitive costs associated with mechanical drying technologies. To address these challenges, two distinct solar drying systems, an indirect solar dryer and a greenhouse solar dryer, were conceptualized, fabricated, and assessed for their drying performance. The design of both dryers employed locally sourced materials, ensuring cost-effectiveness and suitability for rural applications. The indirect solar dryer was constructed with dimensions of 1.23m × 0.57m × 0.21m for the solar collector and a drying chamber measuring 0.85m × 0.525m. In contrast, the greenhouse solar dryer was larger, with dimensions of 1.545m × 1.045m × 1m. This configuration included a raised convection head and a collector plate with dimensions of 1.49 m × 1.02 m to enhance air circulation and drying efficiency. The primary objective of this research was to determine the most effective drying methodology, focusing on key performance parameters such as solar radiation incident on the collector, ambient and chamber temperatures, humidity levels, moisture content of the dried product, and overall drying rates. The drying process was systematically implemented, starting at 8:00 AM and concluding at 4:00 PM each day, over three consecutive days. Results from the drying experiments indicated that the greenhouse solar dryer significantly decreased the moisture content of cassava from an initial value of approximately 79% to a final value of 5%. Meanwhile, the indirect solar dryer showed a comparable reduction, decreasing moisture from 81% to 6%. In contrast, open sun drying, despite achieving a reduction from 95% to 5% over two days, demonstrated considerable quality degradation and risk of contamination due to environmental exposure. The greenhouse dryer recorded peak chamber temperatures reaching 53.6°C, while the indirect solar dryer achieved even higher temperatures of up to 86.1°C in the collector. These temperatures were substantially above the ambient range of 25.2°C to 39.2°C, showcasing the enhanced heating capability of the solar drying systems. The findings of this study highlight the efficacy of solar drying technologies as viable, high-quality alternatives for dehydrating agricultural products, particularly in regions where significant post-harvest losses occur. The advantages of both the indirect and greenhouse solar dryers offer promising solutions tailored to local conditions and resources. Future research is encouraged to focus on optimizing these

drying processes for improved efficiency and product quality across diverse climatic environments, thereby supporting sustainable agricultural practices and food security initiatives.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Agriculture comprises a significant portion of the economies in most African nations, employing 80-90% of the workforce. Despite this extensive involvement in agriculture, food production continues to fall short of meeting the country's demands. A crucial factor contributing to this shortfall is the inadequate preservation and storage systems, resulting in substantial food losses and a pronounced decline in food supply. The challenges posed by crop failures and considerable seasonal fluctuations in food availability can be mitigated through effective food conservation techniques, such as drying. Sun drying is notably the predominant method utilized for food preservation across numerous African countries, attributed to the region's high levels of solar irradiance prevailing for most of the year. However, traditional sun drying methods such as spreading crops on mats, trays, or paved surfaces and exposing them to sunlight and wind have inherent drawbacks. These include the potential for contamination from dust and insects, enzymatic degradation, and microbial infections, which can adversely affect food quality (Ekechukwu and Norton 1999). Furthermore, the traditional process is labor-intensive and time-consuming, requiring crops to be covered at night and during inclement weather, while also necessitating constant vigilance to protect against domestic animals. Inadequate and inconsistent drying results in further crop deterioration during storage, particularly problematic in humid tropical areas where certain crops must be dried during the rainy season. To secure a reliable food supply for the burgeoning population and enable farmers to produce high-quality, marketable products, the development of efficient and cost-effective drying methods is essential. Research indicates that even small-scale, oil-fired batch dryers are not feasible for most farmers due to financial constraints and limited access to energy required for their operation. The high-temperature dryers employed in industrialized nations are economically viable primarily on large plantations or within extensive commercial enterprises. Consequently, the introduction of low-cost, locally manufactured solar dryers presents a viable alternative to significantly reduce post-harvest losses. Producing high-quality marketable goods not only enhances product value but also offers farmers an opportunity to improve their economic circumstances. However, the high initial investment associated with solar dryers remains a formidable obstacle for widespread adoption, given the limited income among rural populations in developing regions (Forson *et al* 2007). The drying process is critical for the preservation of various materials, as it facilitates the evaporation of water or solvents, thereby reducing weight and volume while enhancing product stability and quality. Drying relies on two principal mechanisms of energy transfer: heat transfer, which elevates the temperature of the product to facilitate evaporation, and mass transfer, which enables moisture to migrate from the product’s interior to its surface and subsequently into the surrounding air. Thermal energy, which governs the temperature within a drying system, can be explored within the realm of thermodynamics, focusing on energy transformations in closed systems. This concept encompasses several definitions, including energy at a particulate level, heat transfer, and internal energy or enthalpy. Within rural contexts, sun drying remains a commonplace yet laborious method that risks compromising product quality due to exposure to environmental contaminants. While alternatives like hot air drying can yield superior results, they typically demand significant energy inputs and financial investment, accounting for a considerable portion of industrial energy consumption in developed nations. Solar energy, however, offers a vast and largely untapped potential for drying applications, although challenges in energy capture and storage remain. Historically, sun drying has been widely practiced; however, the industrial demand for more controlled drying processes has surged in 21st-century agriculture, emphasizing the need to maintain product quality(Khouya *et al* 2017).

To improve drying efficiency and product quality, solar dryers have been developed and promoted as sustainable alternatives to traditional methods. These systems utilize solar radiation, a freely available and renewable energy source, to dry crops in a more controlled and hygienic environment. There are three major types of solar dryers: open sun (direct exposure), indirect solar dryers, and greenhouse solar dryers. Each offers varying levels of efficiency, cost, and technical complexity.

Open sun drying exposes agricultural products to environmental elements such as dust, wind, insects, and rainfall, leading to contamination, nutrient loss, and uneven drying (Olayanju et al., 2019). Inconsistent weather conditions further prolong drying times and increase the risk of microbial spoilage. Solar drying technologies have emerged as efficient, sustainable, and hygienic alternatives to traditional open drying (Esper&Muhlbauer, 1996; Janjai, 2012). These technologies harness solar radiation more effectively by controlling the heat transfer process in semi-enclosed environments. They not only improve drying speed but also help retain nutritional quality, prevent contamination, and enhance the visual and sensory attributes of food products (Bala&Mondol, 2001).

Among the types of solar dryers, direct, indirect, and greenhouse dryers have received considerable attention. Each system offers unique structural and operational benefits that affect drying performance and product quality (Forson et al., 2007).

Direct solar dryers allow sunlight to directly contact the food material within a closed transparent box, leading to high drying temperatures but exposing products to potential UV degradation. Indirect solar dryers, in contrast, channel heated air from a solar collector into a separate drying chamber, which protects the product from direct light, allows better temperature regulation, and reduces the risk of oxidative damage (Tiwari et al., 2016).

Greenhouse solar dryers take advantage of the greenhouse effect, using transparent materials to trap solar radiation within a larger enclosure. These systems combine the advantages of both direct and indirect drying while offering better airflow and thermal retention (Sharma et al., 2009). Their design allows for bulk drying of high-moisture crops under relatively stable thermal conditions, even during intermittent solar radiation. Due to their semi-permanent structure and high thermal efficiency, greenhouse dryers are increasingly adopted for drying perishable produce such as tomatoes, cassava, okra, and pepper (El-Sebaii&Shalaby, 2012; Khouya et al., 2017).

Cassava (Manihot esculenta Crantz) stands out as a highly valued agricultural commodity, accounting for approximately 40% of the dietary intake in many developing countries across Africa, Latin America, and Asia (FAO, 2019). The roots of cassava possess a dry matter content of about 30-40%, primarily composed of starch, sugar, and vitamin C, making it integral for animal feed and industrial raw materials. Cassava is predominantly cultivated in the lowland tropical regions along the equatorial belt, bounded by latitudes 30°N and 30°S, and thrives at elevations below 2000 m, with annual rainfall ranging from 200 to 2000 mm (RMRDC, 2004). Notably, Nigeria is the world's largest producer of cassava, contributing over 70% of total production in West Africa and approximately 40% of global output (Deepak and Behura 2025). Cassava chips, which are irregularly sliced dried pieces of cassava, typically measure no more than 5-6 cm in length (Ky *et al.* 2021), while cassava flour represents the most common form in which dried cassava roots are marketed, with exporting countries predominantly producing it.

The drying process for cassava is not merely a preservation technique; it is a crucial step in transforming cassava into safe, storable, and transportable forms. Poor drying practices can lead to mold growth, cyanide retention, and economic loss. Furthermore, inefficient drying contributes to greenhouse gas emissions, as farmers sometimes resort to fuelwood-based methods during the rainy season(Mahmoud *et al 2019*).

In response to these challenges, this project seeks to contribute practical and sustainable solutions by focusing on the design and construction of an indirect solar dryer, specifically tailored to cassava drying in local conditions. It further conducts a comparative thermal analysis between:

- the constructed indirect solar dryer,
- an existing greenhouse solar dryer, and

- the conventional open sun drying method.

The study involves the measurement of solar radiation, drying chamber temperature, ambient temperature, and cassava weight loss over time. These data sets are used to calculate drying rates, moisture loss, and thermal performance, providing an objective basis for comparing the effectiveness of each drying method(Mohammed *et al* 2020).

Beyond its technical objectives, this research aligns with broader global goals:

- It supports climate-resilient agriculture by promoting clean energy solutions.
- It contributes to Goal 2 (Zero Hunger), Goal 7 (Affordable and Clean Energy), and Goal 12 (Responsible Consumption and Production) of the United Nations Sustainable Development Goals (SDGs).
- It empowers rural farmers with accessible technologies that improve product quality, reduce waste, and enhance income.

The project also draws on key principles of physics, especially in thermodynamics (heat and energy transfer), fluid dynamics (airflow through the drying system), and solar energy engineering. By applying these concepts to real-world agricultural problems, the study bridges theoretical knowledge and practical innovation.

In summary, the development and analysis of solar dryers in this project aim to advance low-cost, sustainable, and efficient methods for cassava preservation thereby helping rural communities adapt to modern agricultural demands while preserving traditional crops through science-backed solutions.

1.2 Problem Statement

Cassava (ManihotesculentaCrantz), though highly valuable and widely consumed, remains one of the most perishable staple crops in Nigeria and across sub-Saharan Africa. Within 48–72 hours after harvest, cassava roots begin to deteriorate rapidly due to microbial activity, enzymatic breakdown, and moisture loss. As a result, a significant portion of the harvested cassava is lost before it can be processed, stored, or sold which then contributes to food insecurity, financial loss, and increased post-harvest waste(FAO, 2019; Affognon et al., 2015).

Traditionally, many rural farmers rely on open sun drying as the primary method of cassava preservation. While this technique is easy to implement and cost-free, it is also time-consuming, weather-dependent, and prone to contamination. Crops are often exposed to dust, pests, rainfall, and uneven sunlight, leading to poor drying uniformity, discoloration, microbial infection, and potential toxicity due to retained cyanogenic compounds in improperly dried cassava. These quality issues limit the marketability of cassava and reduce its shelf life, affecting both food safety and farmer income.

To overcome the limitations of traditional sun drying, various solar drying technologies have been introduced. Among these, greenhouse and indirect solar dryers offer promising advantages by providing enclosed, cleaner, and more thermally efficient environments. However, the adoption of these technologies is still limited in many rural areas due to factors such as lack of local fabrication skills, limited performance data, and uncertainty about their comparative effectiveness under different environmental conditions.

Furthermore, while greenhouse solar dryers have gained attention in some regions, there remains a gap in locally developed, low-cost indirect solar dryers designed specifically for cassava and other high-moisture crops. Additionally, few studies have provided detailed thermal performance comparisons among the three main drying methods which are open sun, greenhouse, and indirect systems especially using consistent experimental conditions and real-time measurements of solar radiation, temperature variation, and weight loss over time.

This project seeks to address these issues by designing and constructing an indirect solar dryer using affordable, locally available materials. The dryer’s performance will be evaluated alongside an already existing greenhouse solar dryer and the traditional open sun drying method, with cassava as the test crop. By conducting comparative thermal analysis and calculating moisture loss and drying rates under natural environmental conditions, this study aims to identify the most efficient, practical, and scalable drying solution for rural communities.

In doing so, the project not only contributes to reducing post-harvest losses and improving cassava quality but also supports the transition to renewable energy-based agricultural technologies, especially in the context of rising energy costs, climate variability, and the need for sustainable rural development.

1.3 Aim of the Study

This project aims to analyze and compare the thermal performance of the direct and indirect solar dryers by calculating the moisture loss and drying rate of the cassava.

1.4 Objectives of the Study

The specific objectives of this study are:

- To design and construct a direct solar dryer and an indirect solar dryer.
- To evaluate the thermal performance of the direct and indirect solar dryers by taking hourly measurements of the temperature in the chambers of the dryers.
- To take hourly measurements of the solar radiation.
- To calculate the drying rate of the direct and indirect solar dryers through hourly measurement of the weight of the cassava.
- To carry out a comparative study of the thermal performance of the direct and indirect solar dryers.

1.5 Scope of the Study

This study focuses on the drying of cassava using solar energy as a sustainable alternative to traditional preservation methods. It involves the design and construction of an indirect solar dryer, which is then evaluated alongside an already existing greenhouse solar dryer and the commonly practiced open sun drying method, which in this case is considered the direct drying method.

The choice of cassava as the sample crop is informed by its high perishability and its significant role in the Nigerian diet and economy. By narrowing the investigation to cassava, the study provides a more focused assessment of how solar drying technologies can be applied to reduce post-harvest losses of a staple crop.

The experimental process includes the measurement of key variables such as chamber temperature, solar radiation, and the rate of moisture loss in the drying of cassava. These parameters are monitored at hourly intervals during daylight periods under natural weather conditions, with no additional artificial heat or mechanical airflow introduced. The dryers are tested in a natural outdoor environment to ensure real-life applicability, particularly in rural and off-grid settings.

This work does not extend to the drying of other agricultural produce, nor does it involve the integration of hybrid systems such as electrical or biomass backup. Additionally, microbiological or chemical analysis of the dried product is outside the scope, as the focus remains on the thermal and physical performance of the dryers in terms of temperature behavior, drying time, and weight reduction.

Through this defined scope, the study aims to offer practical insights into the efficiency and suitability of solar drying technologies for cassava processing in rural communities, where access to modern energy and drying equipment is limited.

1.6 Justification of the Study

This study is justified by the growing need to reduce post-harvest losses of cassava in Nigeria, especially in rural communities where farmers rely heavily on traditional methods of drying. Cassava, being highly perishable, begins to deteriorate within 48 to 72 hours after harvest if not properly processed. The most widely used method open sun drying is slow, weather-dependent, and exposes the crop to contamination by dust, pests, and rodents. These limitations often result in poor product quality, reduced shelf life, and economic losses for farmers.

Given these challenges, there is an increasing demand for low-cost, efficient, and sustainable drying systems that can be adapted for use in rural and off-grid areas. While mechanical or fuel-based dryers exist, their high energy requirements and operational costs make them inaccessible to small-scale farmers. In contrast, solar drying technologies provide a renewable, clean, and affordable alternative that can improve both the efficiency and hygiene of the drying process.

This project is particularly relevant because it goes beyond theoretical comparison. It involves the actual design and construction of an indirect solar dryer, using locally available materials, and then evaluates its performance alongside two other drying methods: greenhouse solar drying (using an existing system) and open sun drying (as the conventional method). By analyzing critical parameters such as chamber temperature, solar radiation, and cassava moisture loss, the study offers evidence-based insights into the thermal performance of each system.

Furthermore, the project applies core physics concepts, especially in heat transfer, thermodynamics, and energy conversion, to address a real-world agricultural issue. The practical integration of scientific theory with hands-on experimentation strengthens its academic relevance as a final-year project in applied physics or renewable energy.

In addition to its scientific value, the study aligns with broader developmental priorities such as food security, climate resilience, and rural technology empowerment. The findings have the potential to inform community-level interventions, support farmer cooperatives, and guide policy recommendations for improved post-harvest practices.

In summary, this study is justified by its direct impact on rural livelihoods, its contribution to sustainable energy use in agriculture, and its academic grounding in physical science and engineering principles.

CHAPTER TWO

2.0 LITERATURE REVIEW

A study conducted by Irtwange and Adebayo (2021) investigated the performance of a direct mode natural convection solar dryer designed for drying tomatoes under tropical climate conditions. The researchers constructed a wooden solar chamber enclosed with transparent polythene sheet and mounted a black absorber plate at the base to enhance solar heat capture. Their methodology involved slicing fresh tomatoes and drying them over a 5-day period while monitoring parameters such as ambient temperature, drying chamber temperature, and moisture loss. They observed that the average drying temperature inside the chamber was 42.6°C, significantly higher than ambient, and reported a reduction of moisture content from 92% to 14%. The authors concluded that direct sun drying, though effective, poses limitations such as exposure to dust and pests, suggesting that it be improved with protective enclosures.

Focusing on cassava drying, Mariyappan et al. (2021) developed an indirect forced convection solar dryer equipped with a longitudinal finned solar air heater. Their experiments showed that tapioca moisture was reduced from 64.5% to below 10% within 90 minutes at an airflow rate of 0.03 kg/s. The effective moisture diffusivity was significantly higher in solar drying than in open sun drying, and the thermal efficiency was calculated to be 34.75%. With a payback period of just 1.3 years, the system was deemed economically viable. The study also highlighted the potential for such systems to support rural women involved in cassava processing.

Onoroh et al. (2023) developed a multi-product agricultural dryer that combined solar and biomass energy sources. The system reached drying temperatures of up to 95.7°C and demonstrated efficiency levels around 45%. The authors emphasized the system's ability to function irrespective of weather conditions, providing consistent drying and minimizing contamination risks. They concluded that hybrid dryers offer a practical solution to many limitations of sun drying.

Mujaffar and Lalla (2020) investigated the drying kinetics of cassava chips of varying sizes using a natural convection cabinet dryer. Their results revealed that smaller chip sizes dried more quickly and effectively, achieving final moisture content as low as 2.12% from an initial 61.06%. They successfully applied thin-layer drying models and confirmed that chemical qualities such as cyanide levels remained within safe limits. The study recommended smaller chip sizes for more efficient drying.

Agrawal and Sarkar (2020) presented a comparative thermal analysis of a greenhouse solar dryer and an open sun drying setup for tomatoes in arid regions of India. Their methodology included designing a tunnel-shaped greenhouse dryer using UV-stabilized polyethylene film with forced air circulation, while placing identical tomato slices under open sun simultaneously. Parameters like solar radiation, temperature variation, relative humidity, and drying time were recorded. It was observed that the greenhouse dryer achieved average internal temperatures 10–15°C above ambient and reduced drying time by 40%. The final moisture content reached was 10%, compared to 22% under open sun drying. The authors concluded that greenhouse dryers offer superior protection, faster drying, and better product quality.

Deepak and Behura (2025) conducted a comprehensive thermodynamic and sustainability analysis of a mixed-mode solar dryer that incorporated both sensible and latent heat storage materials to enhance drying performance and energy efficiency. In their design, black pebbles were used for sensible heat storage, while lauric acid served as the latent heat storage medium. The authors observed that integrating these energy storage systems led to a 50% reduction in drying time, as well as significant improvements in thermal performance. Specifically, the dryer achieved a peak energy efficiency of 84.6%, an average energy efficiency increase of 53%, and a maximum energy efficiency of 51.3%, with the average energy efficiency reported at 34.3%. The system also demonstrated a low energy payback period of 1.82 years, and its environmental assessment indicated a CO_2 mitigation potential of 83.97 tonnes per year, equivalent to a carbon credit value of

$419.85. The study concluded that the combined use of sensible and latent thermal storage materials not only improved thermal stability and energy utilization, but also contributed meaningfully to the sustainability and environmental viability of solar drying systems.

Ky et al. (2021) investigated the performance of a sun-tracking–free indirect solar dryer featuring a novel collector design that incorporated hemispherical concentrators and centrally mounted with Fresnel lenses. The system was permanently installed in Ouagadougou, Burkina Faso, and aimed to address post-harvest drying challenges during cloudy seasons, particularly between late May and early June. The authors charged the drying chamber with mango and ginger, placing them on five trays, and monitored weight loss both with and without tray permutation. They reported that the Fresnel lens-enhanced hemispherical concentrators focuses on solar energy efficiency onto a collector with an aperture area of 0.32 m^2, raising tray temperatures to between 57°C and 67°C. Despite operating during a cloudy period, the dryer achieved a collector efficiency of 42.45% and an overall drying efficiency of 41.2%, successfully drying mango within 8 hours. The authors concluded that the innovative collector design significantly improved solar energy capture, offering an efficient and sustainable solution for agricultural crop drying in sub-Saharan regions without the need for sun-tracking mechanisms.

In another study, Adeyanju and Fapetu (2019) constructed and evaluated the performance of an indirect natural convection solar dryer for tomato drying. The system featured a black-painted metal absorber plate, a transparent glass cover, and a drying chamber connected via insulated ducting. Using thermocouples and a digital hygrometer, they recorded the temperature profile across the collector and drying chamber while monitoring weight loss of tomato slices. Their findings showed that the dryer maintained a stable drying temperature range of 40–50°C and achieved 80% moisture reduction within 12 hours, compared to 20 hours for sun drying. The authors observed that indirect dryers reduce product contamination and allow better control of drying conditions.

Chaudhari et al. (2022) explored the design and thermal optimization of a hybrid solar dryer using a combination of solar energy and electrical backup for drying tomatoes. The hybrid system included a flat plate collector, a drying chamber, and a photovoltaic-powered heater for maintaining temperature during cloudy conditions. In their experimental design, tomatoes were dried under three conditions: solar-only, hybrid, and electrical-only modes. It was observed that the hybrid dryer maintained a consistent temperature of 55°C and reduced drying time by 35% compared to solar-only mode. The authors emphasized the role of hybrid designs in ensuring drying reliability in variable weather conditions and recommended it for semi-commercial tomato processing applications.

Obasi et al. (2025) conducted a comparative study on the effects of solar and oven drying (at 50°C and 60°C) on the nutritional and microbiological properties of okra and tomatoes. The study revealed a significant reduction in moisture content post-drying, with solar-dried samples retaining 9.56–16.10% moisture and oven-dried (50°C) samples showing 12.41–17.34%, compared to 28.19–39.04% in fresh produce. Crude protein levels increased in oven-dried samples (17.70–21.71%) compared to fresh samples (13.29–17.93%). Similarly, crude fiber content rose in both solar (4.34–9.42%) and oven-dried (7.21–12.57%) conditions. However, a decline in ash content was noted in oven-dried okra (9.10%) and tomatoes (7.94%), relative to their fresh counterparts. Post-drying, carbohydrate content rose (28.08–50.84% for solar, 29.21–48.16% for oven), while vitamins A and C significantly decreased. Mineral contents (K, Fe, Zn, Ca) increased across all dried samples. Microbiologically, solar-dried products had higher microbial loads, with organisms such as Lactobacillus, Bacillus spp., Pseudomonas spp., and Escherichia coli identified. The authors concluded that oven drying at 50°C better preserves nutritional quality and microbial safety.

Dash et al. (2025) developed a greenhouse solar dryer (GSD) for drying corn in Bukidnon, Philippines, and compared it with open sun drying (OSD). The GSD significantly reduced drying time and moisture content, maintaining lower aflatoxin levels. The system also proved more energy-efficient and cost-effective, indicating its potential for large-scale application. Though their work focused on corn, they suggested that similar systems could be applied to tomato drying, where consistent conditions are essential for quality. They also recommended integrating solar energy and electricity production for cost reduction and promoting environmentally sustainable agriculture.

Okeyode and Okuyelu (2023) designed and fabricated a multi-functional hybrid dryer that utilizes both solar and electric energy sources to dry cassava and red pepper. The performance evaluation was conducted at three temperature levels of 55°C, 60°C, and 65°C to assess drying efficiency and moisture removal. They reported that the system effectively reduced the moisture content of cassava by 84.66%, 89.3%, and 90.62%, while corresponding drying performances were 33.86 kg/hr, 35.71 kg/hr, and 41.43 kg/hr, respectively. For red pepper, moisture reduction levels were 71.51%, 74.5%, and 80.77%, with drying performances of 14.89 kg/hr, 18.63 kg/hr, and 25.24 kg/hr at the same temperature settings. They observed that moisture loss was higher during the initial drying phase and stabilized over time. The system's major components include a blower, heating chamber, solar chamber, and heater, all built within a total material and fabrication cost of approximately $260. The authors concluded that the dryer demonstrated high efficiency, low cost, and was highly suitable for local farmers, offering a practical and scalable solution for post-harvest processing of perishable crops.

Hossain et al. (2018) designed and evaluated a cabinet-type solar dryer in Bangladesh, featuring a collector area of 4.00 m^2 and a drying chamber area of 7.5 m^2, to assess its effectiveness in drying red pepper. They reported that it took 36 hours for red pepper in the upper tray and 41 hours in the lower tray to reduce moisture content from 73% to 10% (wet basis). In contrast, open sun drying required 85 hours to reduce the same moisture content to 11%. The authors found that the system produced 9 kg of dried pepper from 30 kg of fresh produce, compared to 2.43 kg from 8 kg using open sun drying. The study recorded an average global solar radiation of 133 W/m^2, with collector flux absorption at 103 W/m^2.

The collector and dryer efficiencies were 48% and 34%, respectively, while energy efficiency reached 63%. Losses from the top, bottom, and sides of the collector were calculated at 37, 20, and 3 W/m², respectively. The researchers also observed that the color quality of dried pepper was superior in the solar dryer, with redness values (a) of 27.1 and 24.7 for the lower and upper trays, respectively, compared to 21.1 for open sun drying. They concluded that direct sunlight diminishes color quality, and that the cabinet dryer produced higher-quality pepper, faster drying rates, and more efficient energy use.

Njue and Wawire (2021) conducted a study to enhance cassava processing for smallholder farmers in Busia County Kenya, through the development and deployment of a locally fabricated solar dryer. They explained that traditional cassava drying methods typically take 7 to 14 days and are highly prone to contamination from dust, animals, and microbial agents. In their experiment, cassava roots were peeled, washed, sliced using a motorized chipper, and loaded into a solar dryer for evaluation. Temperature readings were recorded at 30-minute intervals during drying. The drying chamber temperatures peaked at 41.7°C on the first day, 49.3°C on the second, and 41.5°C on the third. The initial wet weight of the cassava (4.6 kg) was reduced to a final moisture content of 16% and a dry weight of 1.985 kg after 2.5 days of solar drying. In contrast, the traditional sun-drying method used by local farmers required 10 days to achieve similar dryness. The authors concluded that the fabricated solar dryer significantly reduced drying time and enhanced hygiene, making it an efficient solution for small-scale cassava farmers.

Francis Kumi et al. (2020) evaluated the performance of a chimney-type solar dryer designed to address the limitations of open sun drying in Ghana, particularly for high-value crops such as Habanero pepper (Capsicum chinense). The study, conducted across the Volta, Central, and Ashanti regions, assessed the thermal performance, microbial safety, and quality of solar-dried pepper. The authors reported that during the drying period, the chimney dryer maintained a mean internal temperature of 46.4°C, which was significantly higher than the ambient temperature of 36.2°C. Relative humidity inside the dryer ranged from 25% to 68%, while solar radiation peaked at 823.18 W/m². They recorded a total drying time of 35 hours for the chimney dryer, compared to 55 hours for sun drying. Microbial analysis revealed lower contamination levels in solar-dried samples, with mean yeast and mold counts of 4.30×10^4 cfu/g, compared to 2.52×10^5 cfu/g in sun-dried products. Both Staphylococcus aureus and Escherichia coli were found at negligible levels (<10 cfu/g). The authors concluded that the chimney solar dryer achieved higher thermal performance, faster drying rates, and better microbial safety than open sun drying, offering a cost-effective and hygienic alternative for farmers in developing regions.

A performance evaluation was carried out by Olayanju et al. (2023) on three solar drying methods—direct, indirect, and greenhouse—for drying tomatoes in Southwestern Nigeria. The researchers constructed identical-sized dryers with differing configurations and dried tomato slices under similar climatic conditions. Data collected included chamber temperatures, weight loss, and drying time. Their analysis revealed that the greenhouse dryer had the highest average chamber temperature (47.8°C), followed by the indirect dryer (44.2°C), and the direct dryer (42.0°C). Moisture content was reduced to 12%, 14%, and 17% respectively. It was concluded that while all systems were effective, the greenhouse dryer provided the best drying efficiency and product color retention.

A study by Ndukwu et al. (2020) examined the thermal performance and drying kinetics of a passive solar greenhouse dryer designed for tomato dehydration in Southeastern Nigeria. The researchers constructed a semi-cylindrical greenhouse dryer using transparent polyethylene, with solar absorber trays painted black. Their experimental design involved drying thinly sliced tomatoes over several days, recording hourly temperature, humidity, and weight loss data. The results showed that the greenhouse dryer consistently achieved chamber temperatures 12–16°C above ambient and reduced tomato moisture content from 93% to 14% within 3 days, compared to 5 days under open sun drying. They concluded that greenhouse solar dryers not only enhance drying speed but also maintain better product hygiene and nutritional quality.

Moradi et al, (2025) investigated the drying behavior of potatoes using a hybrid solar dryer equipped with a compound parabolic concentrator (CPC), phase change materials (PCM), and infrared radiation (IR), aiming to optimize energy efficiency and product quality. Drying experiments were conducted at 40°C, 50°C, and 60°C under different PCM and IR configurations. The researchers reported that IR alone reduced drying time by 40%, accelerating moisture removal considerably. However, the inclusion of PCM while improving thermal stability slightly prolonged drying due to its heat absorption characteristics. Among all tested combinations, 60°C with both PCM and IR produced the shortest drying time, the lowest specific energy consumption (SEC), and minimized color change (ΔE), confirming it as the optimal configuration. At this setting, drying time was further reduced by an average of 5.3%, while energy and energy efficiencies improved significantly. The authors concluded that integrating PCM and IR technologies into hybrid solar dryers enhances drying kinetics, stabilizes thermal conditions, and maintains product quality, and they recommended future studies to explore microwave and ultrasound-assisted drying to further boost system performance.

Nwakuba and Anyaoha (2020) conducted an extensive optimization study on the drying of red pepper slices using a hybrid photovoltaic-thermal (PV/T) solar dryer in a humid tropical region of Nigeria. Their research employed a response surface methodology (RSM) using a 3^3 factorial design to analyze how drying air temperature, air velocity, and sample thickness affected drying parameters such as energy consumption, drying time, shrinkage, and efficiency. The authors evaluated air temperatures of 50, 60, and 70°C; air velocities of 1.0, 1.5, and 2.0 m/s; and sample thicknesses of 10, 15, and 20 mm. They reported that the optimal drying conditions were at 70°C, 1.88 m/s, and 14.31 mm sample thickness, achieving a desirability score of 0.903. Under these conditions, total energy consumption was 4.03 kWh, system drying efficiency 20.46%, shrinkage 67.05%, and drying time 183.8 minutes. The R^2 values for their predictive models ranged between 0.9228 and 0.9989, confirming their accuracy and reliability. They further noted that contributions from the

PV module and solar collector to total energy varied significantly, with Qpv between 0.792–23.53% and Qcol between 0.518–15.37%. The study concluded that optimization techniques are indispensable in improving the performance of hybrid solar dryers, especially under fluctuating solar and humid wind conditions common in tropical climates.

Bala et al. (2018) analyzed the performance of a solar tray dryer for cassava starch. Their findings showed a decrease in moisture from 50% to 8% within a short drying period, with internal temperatures reaching 60°C. The thermal efficiency of the dryer was recorded at 40%, and relative humidity dropped to 30%, demonstrating the system's capacity to maintain a controlled drying environment.

Fudholi et al. (2018) carried out a thermal efficiency analysis of a double-pass solar collector integrated with an indirect dryer for tomato dehydration. The system was tested under Malaysian tropical conditions, where the tomato slices were placed in a drying chamber connected to a solar air heater with two air channels. Using digital anemometers, thermocouples, and data loggers, the researchers monitored inlet/outlet temperatures, airflow, and moisture loss. They observed that the double-pass configuration resulted in higher heat retention and faster moisture removal, achieving final moisture content below 15% within 10 hours. The authors reported that thermal efficiency peaked at 61.2% and recommended the system for improving solar drying performance in humid climates.

In an experimental study conducted by Rajput et al. (2019), the performance of a cabinet-type solar dryer was compared with traditional sun drying for tomatoes. The cabinet dryer was made of wood and transparent glass, equipped with ventilating holes and metallic trays. The research team evaluated moisture content, drying time, and microbial load. It was found that the cabinet dryer dried tomato slices to 13% moisture content in 14 hours, whereas sun drying took over 24 hours. Additionally, microbial load was significantly lower in the cabinet-dried samples. The study concluded that cabinet dryers are practical for small-scale tomato processors, offering improved drying efficiency and hygiene.

Onyebuchi et al. (2021) designed and analyzed a forced convection indirect solar dryer with a solar collector plate and a DC fan powered by a small PV panel. The system was applied to tomato drying during off-peak sunshine periods. In their approach, tomatoes were dried over a 3-day period, with airflow and temperature regulated by the fan. The study recorded improved drying rates, with internal dryer temperatures reaching up to 52°C. It was observed that the forced airflow accelerated moisture loss and reduced drying time by about 25% compared to natural convection designs. The authors concluded that incorporating PV-powered fans enhances system efficiency in low-insolation regions

According to Sharma and Kumar (2022), a tray-type indirect solar dryer was developed and its thermal performance evaluated for tomato slices in northern India. The dryer consisted of an aluminum absorber plate painted black, enclosed in a glass cover, with drying trays made of stainless steel mesh. The experiment compared dryer output on sunny versus cloudy days. The average collector efficiency ranged from 35% to 48%, and tomatoes were dried to a safe storage moisture level of 13% within 12 hours on sunny days. The authors noted significant quality retention in color and texture and recommended the system for domestic tomato preservation.

In a performance optimization study, Yusuf and Okonkwo (2020) analyzed the impact of absorber plate materials on the thermal behavior of an indirect solar dryer used for drying tomatoes. The authors tested three absorber plates; aluminum, mild steel, and copper under identical drying conditions. Tomatoes were sliced uniformly and loaded into the drying chamber, and thermal data were collected using thermocouples and data loggers. It was observed that the copper plate produced the highest drying temperatures, leading to faster drying (11 hours) compared to mild steel (13 hours) and aluminum (15 hours). The study concluded that material selection plays a significant role in improving dryer efficiency, especially when designing cost-effective systems for tomato preservation.

Mahmoud and El-Sebaii (2019) carried out an experimental and theoretical study of tomato drying kinetics in a natural convection greenhouse dryer. The dryer was constructed using a semi-circular polycarbonate enclosure with ventilators and black aluminum flooring to enhance thermal capture. The authors used thin-layer drying models to fit the moisture ratio data against drying time. Results indicated that the Page and Modified Henderson models best described the drying behavior. Drying time was reduced by 30% compared to open sun drying, with consistent internal temperatures around 50–60°C. The authors concluded that combining modeling with experimental testing aids in predicting drying performance and optimizing dryer geometry.

Rahman et al. (2021) developed and tested a solar tunnel dryer for rural tomato farmers in Bangladesh, focusing on affordability and efficiency. The system consisted of a long tunnel-shaped chamber, covered with UV-stabilized polyethylene film and fitted with passive vents. Tomatoes were pre-treated with salt to improve drying uniformity, and drying was conducted over a 3-day period. Observations showed that the tunnel dryer maintained internal temperatures 8–12°C higher than ambient, and achieved over 85% reduction in moisture content within 24 hours of effective sunshine. The authors concluded that the design offered a scalable solution for post-harvest losses among smallholder tomato producers.

Bala and Mondol (2018) conducted a thermal and economic evaluation of a solar photovoltaic (PV) powered forced convection greenhouse dryer for tomatoes. Their experimental setup included PV panels connected to a DC blower that ensured continuous airflow inside the greenhouse. Tomatoes were dried over a period of 2–3 days and monitored for drying rate, energy use, and payback period. The study observed that while the capital cost was higher than passive systems, the drying was faster and more uniform, with significant energy savings over time. The authors recommended PV-assisted systems for long-term sustainable tomato drying, especially in commercial operations.

A study by Eze and Agbo (2023) focused on improving tomato drying performance using a dual-mode solar dryer that combines direct and indirect heating mechanisms. The dryer consisted of a solar collector unit and a transparent drying chamber that received both direct sunlight and warm air from the collector. The experiment involved drying fresh tomatoes under natural conditions and monitoring chamber humidity, temperature, and weight loss.

The study found that the dual-mode design maintained temperatures between 45°C and 58°C, and drying was completed within 10 hours. The authors concluded that combining drying modes enhances heat transfer and reduces energy losses, especially in cloudy weather conditions.

Ahmed et al. (2022) designed a compact, portable solar dryer for household tomato drying, emphasizing low-cost materials and ease of deployment. The design integrated a small inclined solar collector, drying trays, and a clear acrylic cover. Tomatoes were pre-treated with a blanching process and spread evenly on mesh trays. The researchers monitored temperature and humidity variations using digital sensors. Observations indicated that the internal drying chamber temperature reached up to 50°C on sunny days, with drying completed in 14 hours. The authors concluded that the portable system provides a practical solution for domestic users, improving hygiene and reducing spoilage without reliance on electricity.

In another study, Ismail and Ibrahim (2021) explored the efficiency of a solar biomass hybrid dryer for drying tomatoes in semi-arid regions. The system combined solar energy during the day and biomass fuel (wood) as backup heat during nighttime. Tomatoes were dried over 48 hours, with biomass heat applied in the evenings to maintain chamber temperature. Results showed consistent drying, with moisture content reduced to below 12%. The hybrid system ensured continuous drying and reduced weather dependency. The authors emphasized the benefit of hybridization in improving productivity and recommended the approach for remote agricultural regions lacking grid access.

Patomsok (2014) explored the use of a hybrid microwave-hot air dryer for cassava slices. He observed that the drying time decreased significantly as surface temperature increased, completing drying within 300 minutes at 80°C. Moisture removal exceeded 87%, and the Page and diffusion models were identified as the best fit for predicting moisture ratios. The hybrid system was recommended for improved drying speed and product quality.

Kareem et al. (2020) carried out a comparative assessment of open sun drying and indirect solar drying using a cabinet-style dryer. The study involved slicing tomatoes into uniform thickness and placing equal masses in the sun and dryer. Temperature, humidity, and weight loss were recorded hourly. It was observed that the indirect dryer reached 45°C, while sun drying averaged 33°C. The indirect system achieved complete drying in 10 hours, while sun drying took over 20 hours. The authors concluded that indirect solar dryers offer better efficiency, reduced drying time, and improved quality, especially in urban settings where space and sanitation are critical.

Serm (2012) contributed to the development of large-scale greenhouse-type solar dryers intended for small-scale food industries. His design featured a parabolic roof covered in polycarbonate material and incorporated a 100 kW LPG backup heater along with photovoltaic-powered ventilated fans. According to his findings, the dryer reduced the drying duration of osmotically dehydrated tomatoes by 23 days compared to open sun drying. Furthermore, the product quality was significantly enhanced. He concluded that greenhouse solar dryers are scalable, cost-effective, and suitable for tropical climates.

Solomon and Tesfaye (2019) evaluated a solar dryer equipped with an internal thermal mass (stones) to retain heat after sunset. The design aimed to extend drying hours in regions with fluctuating sun intensity. Tomatoes were loaded during the day, and chamber conditions were tracked into the evening. Observations showed that the thermal mass maintained drying temperatures above 30°C for up to 3 hours after sunset. Moisture content dropped to safe levels within 24 hours, compared to 36 hours without thermal storage. The authors concluded that incorporating thermal mass in solar dryers improves efficiency and helps bridge night-time cooling effects.

Ogbonna et al. (2023) investigated microbial load and nutritional changes in tomatoes dried using direct sun and solar cabinet dryers. Samples were collected at intervals and analyzed for bacterial and fungal counts as well as vitamin C retention. The cabinet dryer achieved a 95% reduction in microbial load compared to sun drying and retained 72% of vitamin C, while open sun drying retained only 49%. The authors concluded that solar cabinet dryers not only improve thermal performance but also preserve nutritional quality and food safety.

Daramola and Adesina (2022) conducted an experimental study on the effect of pre-treatment on drying kinetics using a direct solar dryer for tomatoes. Tomato slices were divided into three groups: untreated, salted, and blanched. All samples were dried using a locally fabricated wooden dryer with a transparent plastic cover. The researchers measured drying time and final moisture content. It was found that blanched tomatoes dried faster and retained a brighter color, with final moisture content of 13% compared to 18% in untreated slices. The authors concluded that appropriate pre-treatment enhances drying efficiency and post-drying quality in direct solar drying systems.

Rani and Verma (2023) examined the influence of air circulation on the drying rate of tomatoes in a forced convection solar dryer. The system was designed with a DC fan powered by a photovoltaic panel, ensuring consistent airflow across the trays. During the trials, the researchers recorded temperature, humidity, and airflow rate at different fan speeds. It was observed that an airflow rate of 1.5 m/s resulted in optimal drying, completing the process in 10 hours while minimizing case hardening. The study concluded that controlled air circulation significantly improves drying uniformity and energy efficiency in solar dryers.

In an investigation by Egunjobi et al. (2020), the performance of an indirect solar dryer was evaluated under varying climatic conditions in Lagos, Nigeria. The researchers measured solar radiation, chamber temperature, and drying rate over a one-week period with changing weather patterns. The dryer was constructed with a metal collector plate and insulated drying cabinet. It was observed that the system remained functional even under cloudy skies, maintaining a minimum internal temperature of 35°C. Moisture content was successfully reduced to below 15%. The authors recommended the system for coastal regions where inconsistent sunlight is common.

Abdullahi et al. (2021) developed a mathematical model to predict drying behavior in indirect solar dryers and validated it with experimental data from tomato drying. Using finite difference methods and heat transfer equations, the model simulated temperature and moisture movement in the drying chamber. Experimental data were collected using thermocouples and digital scales. The model showed good agreement with actual results, with less than 10% error in predicting drying time. The study concluded that mathematical modeling supports system design and helps in optimizing operational parameters for better thermal efficiency.

Finally, Tagoe and Opoku (2023) assessed energy and economic performance of three types of solar dryers; direct, indirect, and hybrid deployed in tomato farming cooperatives. The analysis involved monitoring energy input (solar insolation), output (moisture loss), and calculating cost-per-kilogram of dried tomatoes. It was observed that the hybrid dryer had the highest energy efficiency (58%) and the lowest operating cost per kg. Although the initial cost was higher, the payback period was shorter due to increased productivity. The authors concluded that hybrid dryers offer the best return on investment for small agribusinesses targeting commercial tomato drying.

2.1. Solar Drying Technology

Solar drying has been used since time immemorial to dry plants, seeds, fruits, meat, fish, wood, and other agricultural, forest products. In order to benefit from the free and renewable energy source provided by the sun several attempts have been made in recent years to develop solar drying mainly for preserving agricultural and forest products. However, for large scale production the limitations of open air drying are well known. Among these are high labour costs, large area requirement, lack of ability to control the drying process, possible degradation due to biochemical or microbiological reactions, insect infestation, and so on. The drying time required for a given commodity can be quite long and result in post-harvest losses(more than 30%). Solar drying of agricultural products in enclosed structures by forced convection is an attractive way of reducing post-harvest losses and low quality of dried products associated with traditional open sun drying methods (Njue and Wawire 2021). In many rural locations in most developing countries, grid connected electricity and supplies of other non-renewable sources of energy are either unavailable, unreliable or, too expensive. In such conditions, solar dryers appear increasingly to be attractive as commercial propositions (Ndukwu *et al.*, 2020).

During the last decades, several developing countries have started to change their energy policies toward further reduction of petroleum import and to alter their energy use toward the utilization of renewable energies. With very few exceptions, the developing countries are situated in climatic zones of the world where the insolation is considerably higher than the world average of 3.82 kWh/m 2 day. In Figure 2.1 daily average horizontal insolation data and sunshine hours of some developing countries are given. An alternative to traditional drying techniques and a contribution toward the solution of the open air drying problems is the use of solar dryers. Accordingly, the availability of solar energy and the operational marketing and economy reasons offer a good opportunity for using solar drying all over the world.

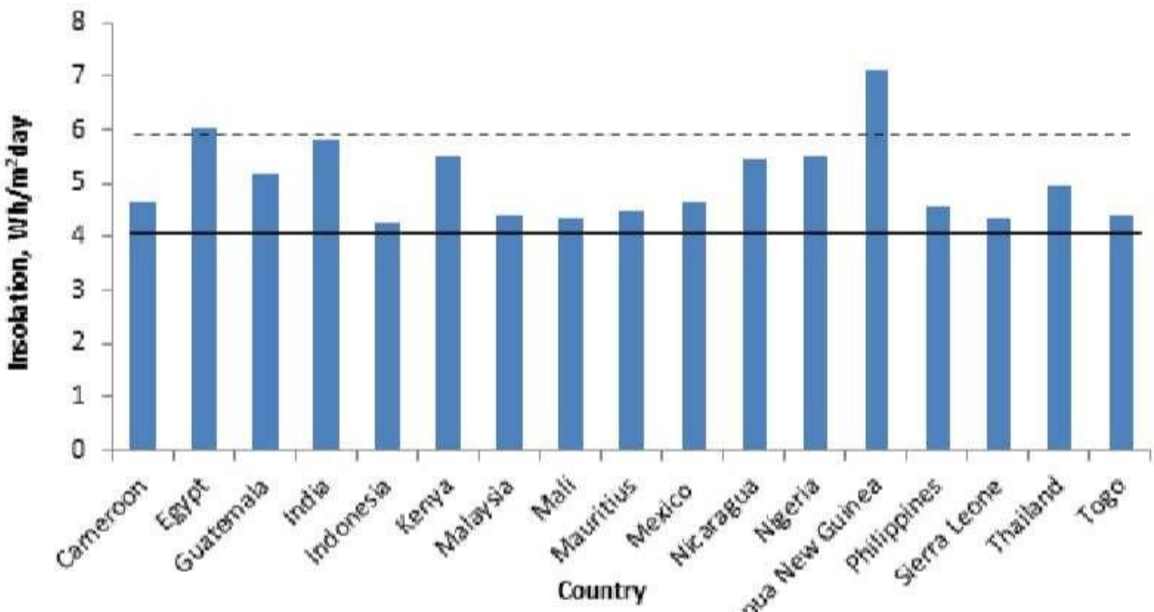


Figure 2.1. Total horizontal solar insolation for some developing countries

2.2. Classification of Solar Dryers

Solar dryers are typically classified based on their design configuration and mode of air circulation. The two major classifications are passive solar dryers, which rely entirely on natural convection and solar radiation without auxiliary energy, and active solar dryers, which utilize mechanical or electrical components such as fans and heaters to enhance airflow and control conditions within the drying chamber. This classification plays a vital role in determining the dryer's efficiency, cost-effectiveness, and suitability for various agricultural or industrial applications.

2.2.1 Passive Solar Dryers

Passive solar dryers are systems that utilize the natural movement of heated air generated by solar radiation for the drying process. These dryers do not require external power sources or mechanical aids, which makes them ideal for smallholder farmers and rural settings where electricity is scarce or unavailable. Passive solar dryers are further divided into two main types: direct and indirect solar dryers.

- Direct Passive Solar Dryer: The direct solar dryer operates on the principle of directly exposing the product to solar radiation within an enclosed transparent chamber. The transparent cover (usually made of glass or clear plastic) allows sunlight to pass through and heat the product directly, while also trapping thermal radiation inside the chamber, increasing the internal temperature and facilitating moisture evaporation (Hossain &Bala, 2007). This system typically consists of a drying chamber, mesh trays, and a transparent roof or top surface. Although effective in raising the drying temperature, this method exposes the product to ultraviolet radiation, which may degrade certain nutrients or pigments. It also requires frequent monitoring to prevent overheating and ensure uniform drying.

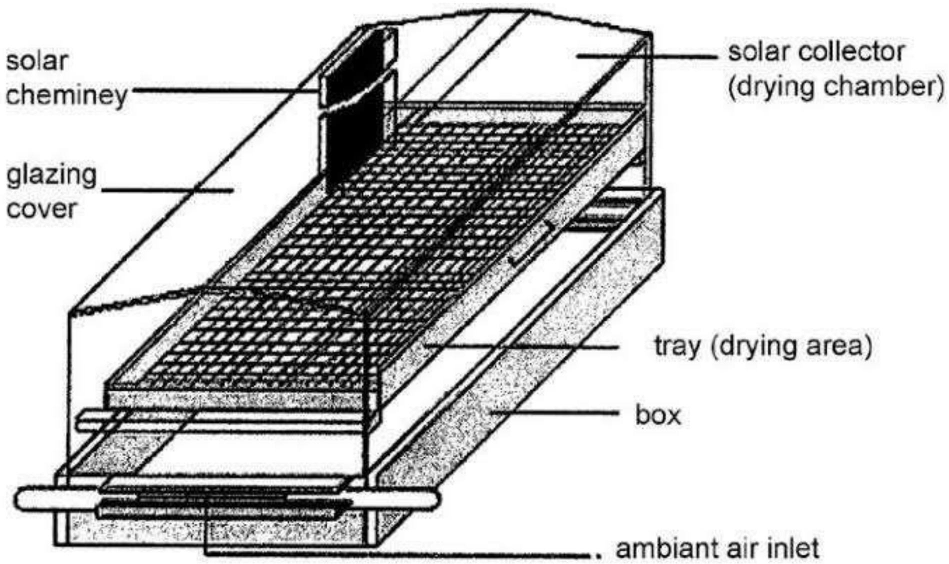


Figure 2.2.1.1: Layout of a Direct Passive Solar Dryer

The major advantage of this system is its simplicity and low construction cost. However, it is limited by factors such as uneven drying and vulnerability to weather changes. Studies by Fudholi et al. (2014) confirm that direct passive dryers are best suited for crops like tomatoes and pepper when applied in areas with high solar intensity and stable weather.

- Indirect Passive Solar Dryer: In the indirect passive solar dryer, solar energy is first used to heat air in a solar collector before channeling it into the drying chamber where the product is kept. This configuration prevents direct exposure of the product to sunlight, thus preserving its color, flavor, and nutrients. The natural convection current created as the hot air rises draws cooler air from the inlet, facilitating continuous airflow through the system (Esper&Mühlbauer, 1998).

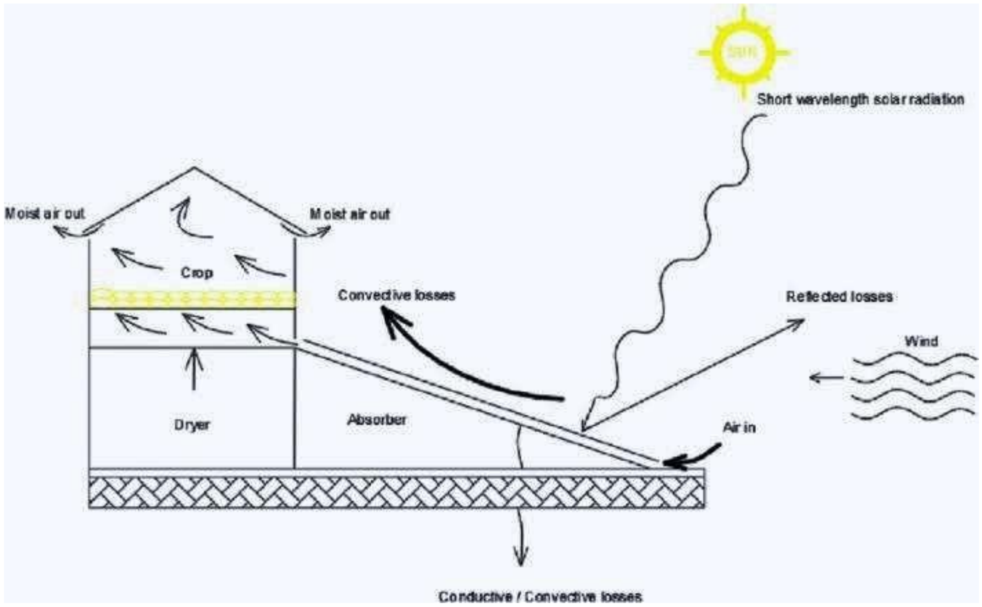


Figure 2.2.1.2 : Layout of an Indirect Passive Solar Dryer

This type of dryer enhances hygiene and reduces contamination risk, which makes it suitable for delicate crops such as herbs, spices, and leafy vegetables. Research by Bala and Woods (2001) noted that while indirect passive dryers may take slightly longer drying times compared to direct dryers, the product quality tends to be superior due to the absence of direct sunlight.

2.2.2 Active Solsr Dryers

Active solar dryers incorporate mechanical components to boost the movement of heated air and regulate drying conditions, thereby ensuring faster and more uniform drying. These systems usually include fans, blowers, or photovoltaic-powered ventilation systems and are more technologically advanced than passive systems. They are further classified into indirect active, hybrid, and other integrated solar dryer designs.

- Indirect Active Solar Dryer: In this system, solar energy heats air in a collector, and then a fan or blower pushes the heated air into the drying chamber. The airflow is controlled to maintain a consistent drying rate, reducing the risk of mold growth or spoilage. Unlike passive systems, indirect active dryers can operate under cloudy conditions or at night when coupled with thermal storage units (Madhlopa&Ngwalo, 2007).

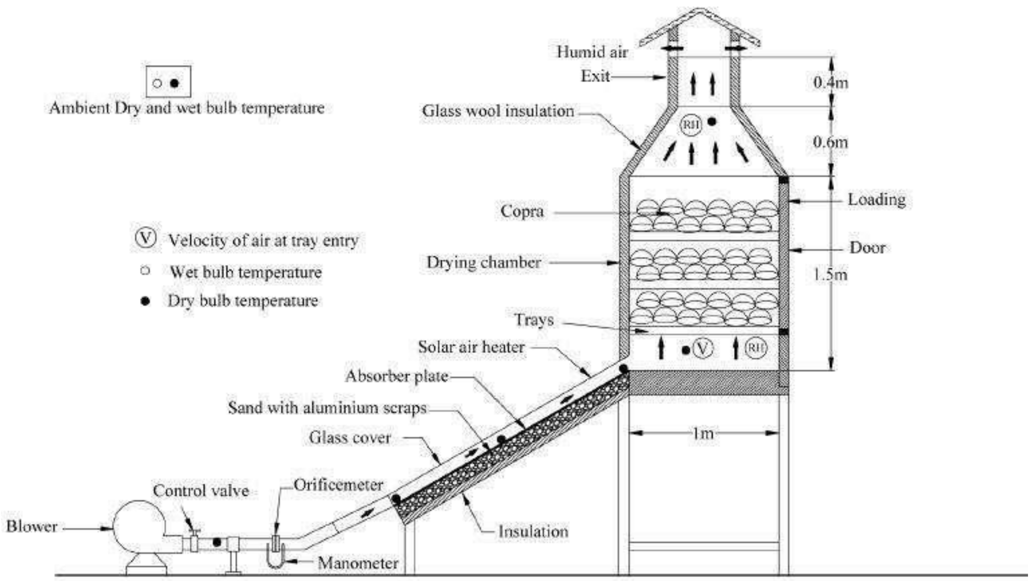


Figure 2.2.2.1: Layout of an Indirect Active Solar Dryer system

According to Janjai and Bala (2012), the major advantage of indirect active dryers is their ability to maintain higher temperatures and better control humidity levels, resulting in shorter drying durations and higher efficiency. They are ideal for high-value crops such as tomatoes, okra, and medicinal plants.

- Hybrid Solar Dryer: Hybrid solar dryers combine solar energy with auxiliary heating sources such as electric heaters, LPG burners, or biomass stoves to ensure uninterrupted drying regardless of weather conditions. These dryers often include photovoltaic cells to power fans or heaters, thereby integrating renewable energy with mechanical aids for optimized performance (Hussein et al., 2017). The hybrid model is particularly useful in areas with variable weather patterns or high humidity.

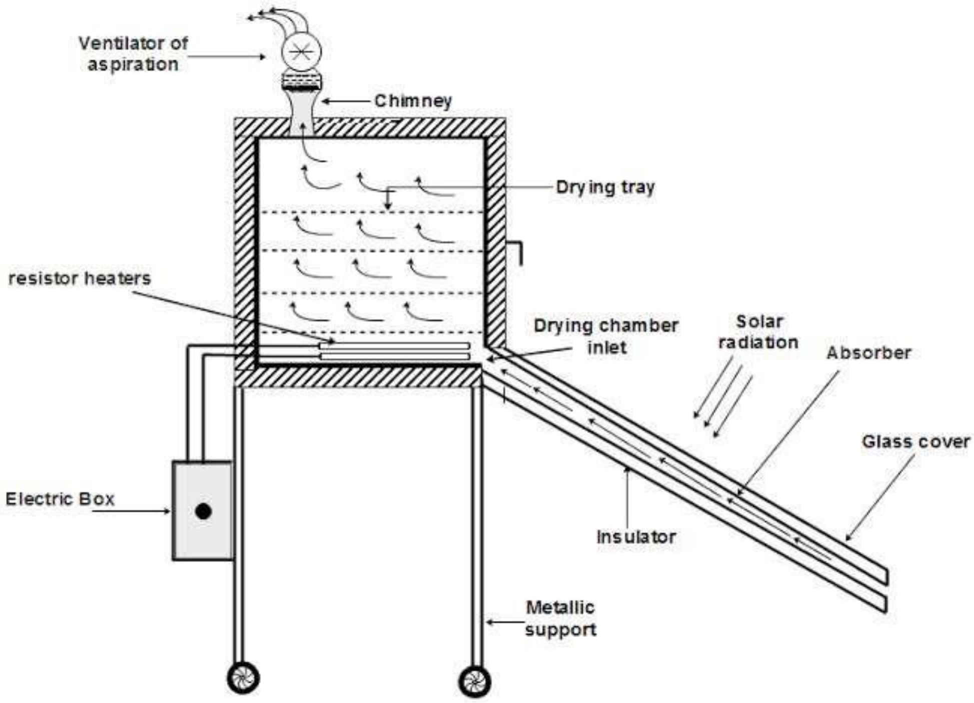


Figure 2.2.2.2: Layout of Hybrid Solar Dryer

Studies by Elwakeel et al. (2024) demonstrated that hybrid dryers achieved moisture reductions of up to 80% within 6–8 hours, significantly outperforming passive systems. The incorporation of backup systems ensures that product quality is preserved, and operational efficiency is not weather-dependent.

2.3 Working Principle and physics of Indirect Solar Dryer

The indirect solar dryer is a drying technology that utilizes solar radiation to generate heated air in a separate collector unit, which is then channeled into an insulated drying chamber. Unlike direct drying systems where products are exposed to sunlight, the indirect method protects agricultural produce such as pepper from harmful ultraviolet rays, dust, and contaminants, thereby improving drying quality and hygiene. The thermal performance of this system hinges on the interplay between solar radiation, air convection, insulation, and moisture diffusion from the product surface. In this study, the indirect solar dryer employed a natural convection approach, relying on the natural buoyancy of hot air rather than mechanical air movement.

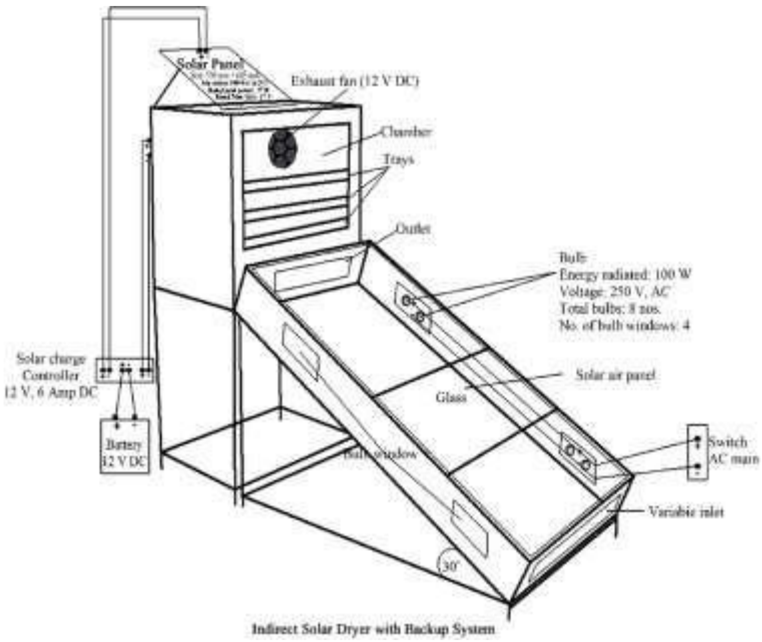


Figure 2.3.1: Indirect Solar Dryer with Backup System

Figure 2.3.1 illustrates a more advanced configuration of an indirect solar dryer, featuring a backup system composed of a solar panel, battery, and DC exhaust fan. The solar collector in this design is a sloped, glazed enclosure that captures solar energy, which is then converted into thermal energy by internal black-painted absorbing surfaces. The hot air generated inside the collector flows upward due to density differences and enters the drying chamber through a channel.

The drying chamber contains multiple trays arranged vertically, where sliced agricultural produce is spread in thin layers. A 12 V DC exhaust fan installed at the top of the chamber assists in drawing the hot air uniformly over the trays and expelling the moist air through an outlet. The fan is powered by a solar panel that charges a 12 V DC battery via a solar charge controller. For night-time or low-radiation support, the system includes 100 W bulbs installed within “bulb windows” to provide thermal backup and ensure continuous drying, particularly in humid or cloudy weather.

This design ensures enhanced airflow, temperature stability, and reduced drying time. However, it is important to note that the system constructed in this present study did not incorporate electrical backup or forced convection elements. Instead, the fabricated dryer was designed to operate under natural convection, with airflow driven solely by thermal gradients between the collector and the outlet vent.

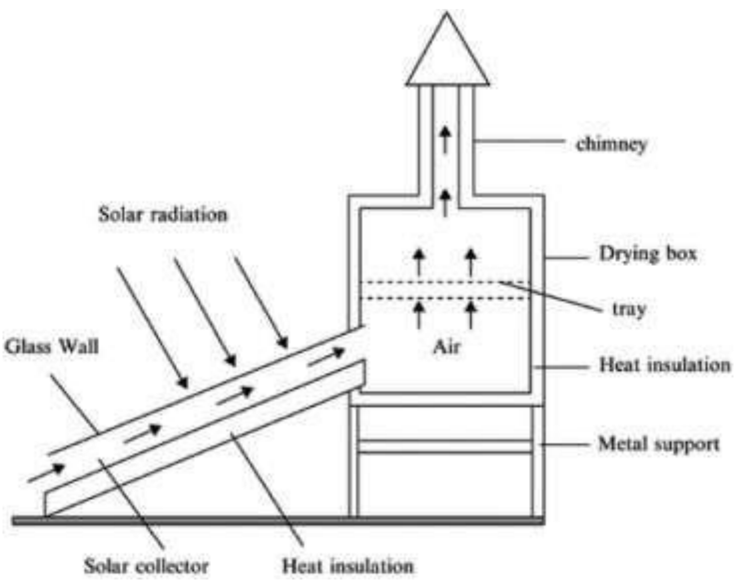


Figure 2.3.2: Basic Indirect Solar Dryer (Without Backup System)

Figure 2.3.2 presents a more conventional or passive indirect solar dryer, resembling the one constructed in this study. The primary components of this dryer include a slanted solar collector, a drying chamber, a chimney for air exit, and supporting frames. Solar radiation passes through the transparent glazing (glass wall) of the collector and strikes the absorber plate beneath it. The absorber typically black-coated metal or aluminum converts solar radiation into heat, warming the air inside the collector channel.

As the air is heated, its density decreases, causing it to rise naturally into the drying chamber. This continuous movement of hot air creates a natural draft effect, promoting the flow of air through the trays where the product is laid. Moist air rises further and escapes through a chimney placed at the top of the drying box. This chimney effect improves air circulation and maintains the drying gradient necessary for continuous moisture removal.

In the system used for this research, the indirect solar dryer was constructed using an iron skeleton structure, covered with HDF plywood board and transparent glass (10mm inner and 5mm outer layer) on the collector side. The absorber was painted black for enhanced heat absorption, and the inner trays were plastic (non-metallic), placed on a fixed iron rack inside the chamber. The construction excluded fans, bulbs, solar panel, or any electrical components.

To better appreciate the operation of the indirect solar dryer, it is important to understand the role of each component and the physical principles they embody:

- Solar Collector: The collector is the heart of the system. It converts solar radiation into thermal energy through a process of radiation absorption. Solar rays penetrate the transparent glass layer and are absorbed by a dark-colored metal sheet. This sheet, with high absorptivity and low reflectivity, transfers heat to the air trapped within the enclosed collector. The transparent glass also acts as a cover that reduces convective heat loss and enhances the greenhouse effect, allowing sunlight in while reducing re-radiation of heat out.The slant angle of the collector (30° in the backup system diagram) is designed to maximize solar exposure depending on the latitude of the location (in this case, southwestern Nigeria). As the temperature rises, the less dense air becomes buoyant and begins to flow into the adjacent drying chamber.

- Drying Chamber and Trays: The drying chamber is a thermally insulated enclosure where pepper slices are spread on trays. These trays are perforated (if metal) or open (if plastic) to permit even distribution of hot air across the sample. The primary mechanism of moisture removal here is convection: the heated air transfers energy to the pepper, raising its surface temperature and facilitating evaporation of moisture.Heat conduction from the tray into the pepper, and evaporation of water from the internal cells toward the surface, are enhanced by consistent air movement. The chamber is typically coated or lined to retain heat and minimize losses through conduction.
- Chimney or Outlet Vent: In passive systems, the chimney serves a crucial role in facilitating natural convection. As hot moist air accumulates in the drying chamber, it becomes lighter and escapes through the chimney, drawing fresh hot air from the collector. This creates a continuous airflow cycle that maintains the drying environment. The height and width of the chimney can significantly influence airflow velocity and drying rate.
- Insulation and Structural Materials: Thermal insulation (e.g., fiberglass, foam, or wood board) is used to reduce heat loss to the surroundings, especially from the sidewalls and base of the drying chamber. The materials selected for construction must be durable, non-toxic, and stable under high temperatures. In the constructed unit, wood was used for paneling, and joints were sealed to prevent leakage. All

internal parts were painted black to enhance absorption, and aluminum angle iron was used to prevent water ingress between glass and frame joints during rain.

- Air Movement Mechanism: In the backup-supported version, airflow is mechanically enhanced by an electric fan that operates on solar power or battery charge. This increases airflow rate and drying efficiency, especially in high-humidity conditions or during low solar radiation. In contrast, the passive version depends solely on thermal buoyancy, warm air rising and cool air being drawn in to maintain airflow. Though less aggressive, it is effective and more energy-efficient.
- Backup Heating (Bulbs): In the advanced system (Figure 2.1), the inclusion of bulbs as a thermal backup ensures the drying process can continue during cloudy days or at night. These bulbs emit heat, not light, and are typically arranged at strategic locations within the collector to maintain air temperature.However, this adds to the operational cost and energy dependency, which is why it was excluded from the built version used in this study.

Both configurations of the indirect solar dryer operate on the same underlying physical principles: capture of solar radiation, conversion into heat, transfer of heat to airflow, and removal of moisture through evaporation and ventilation. However, the presence of a fan, battery, and electrical heating backup in the advanced model allows for enhanced efficiency, shorter drying times, and controlled conditions.

The constructed system used in this study adhered to the passive model (Figure 2.2), which though is slower, is more sustainable and cost-effective for rural or low-resource settings. It was successfully used to dry pepper, with hourly temperature and moisture readings taken to evaluate performance across multiple days.

The effectiveness of an indirect solar dryer is governed by three primary modes of heat transfer: convection, conduction, and radiation, all of which work synergistically to dry the agricultural produce.

- Convection is the dominant mechanism in the indirect drying process. As solar radiation heats the air in the collector, the air becomes lighter (less dense) and rises naturally into the drying chamber. This upward flow of warm air is what drives moisture removal from the pepper slices placed on the trays. As the warm air contacts the moist pepper surfaces, it absorbs moisture, creating a vapor-rich environment that continues to move upward and is eventually vented through the outlet or chimney. In systems with fans (as seen in Figure 2.1), this airflow is mechanically accelerated, leading to faster drying. In the naturally ventilated model used in this study (Figure 2.2), convection occurs passively, relying on the buoyancy effect created by temperature gradients.
- Conduction, while less dominant, plays a critical role in the initial transfer of thermal energy from the hot air or heated tray surfaces into the pepper slices. As the hot air bathes the trays, heat is conducted through the tray material (especially if metallic) and into the lower layers of the pepper. The internal moisture within each slice also migrates toward the surface through molecular conduction, after which it evaporates into the air. Although conduction is a slower process compared to convection, it is essential for drying the inner tissues of the pepper.
- Insulation acts as a thermal barrier that prevents heat loss from the system to the external environment. In the constructed dryer, insulation was achieved by using fiber material between the chamber walls and by minimizing heat bridges at the joints. This ensured that the majority of the heat energy captured remained within the system to support evaporation, rather than dissipating through structural leakage. Proper insulation improves the thermal efficiency of the system and reduces temperature fluctuations that may slow down drying.

Collectively, these heat transfer modes ensure a continuous cycle: radiation heats the air, convection carries the heat to the drying chamber, conduction transfers it to the pepper, and insulation retains the thermal energy in which all contributes to efficient moisture removal.

2.4 Working Principle and Physics of Greenhouse Solar Dryer

The greenhouse solar dryer is a modified greenhouse structure used for drying agricultural products by trapping solar radiation and creating a warm, enclosed environment that enhances moisture removal. It is particularly effective in reducing post-harvest losses, improving product hygiene, and providing a consistent drying environment irrespective of fluctuating external weather conditions.

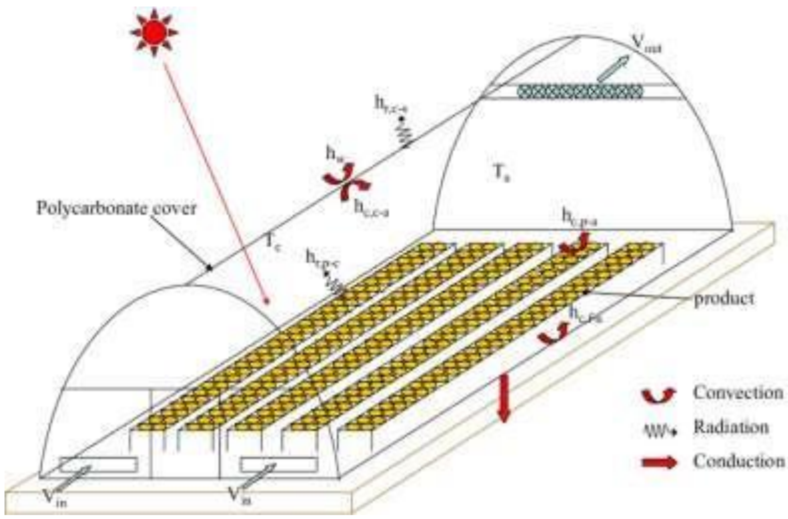


Figure 2.4.1: Working Principle of a Greenhouse Solar Dryer

Figure 2.4.1 illustrates the basic configuration and thermal behavior of a typical greenhouse solar dryer. The structure consists of a transparent polycarbonate cover that allows incoming solar radiation to penetrate the drying chamber. This cover is responsible for creating the greenhouse effect, whereby shortwave solar radiation enters the dryer, heats up internal surfaces, and is then re-radiated as longwave infrared energy that becomes trapped, increasing the internal temperature of the chamber.

The diagram features thermodynamic elements labeled as convection, radiation, and conduction to represent the different modes of heat transfer active within the dryer:

Radiation is the initial energy input, where sunlight directly enters through the transparent cover and heats the air, floor, and any black-painted surfaces inside the dryer. These surfaces then emit longwave infrared radiation, which is partially trapped inside the chamber, contributing to the internal heat buildup.

Convection occurs as the heated air inside the chamber becomes less dense and begins to rise. Cooler air from the bottom is drawn in to replace the rising hot air, creating a continuous flow cycle. This natural air circulation enhances the transfer of moisture from the surface of the product into the air stream.

Conduction is responsible for the transfer of heat through solid materials such as the floor, tray holders, and metallic parts of the frame. As these materials heat up from radiation, they pass thermal energy into the produce that is in direct contact with them. This aids in drying from the underside of the product, complementing the convective drying above.

The airflow in the system is represented by V-in and V-out, indicating the air inlet and outlet, respectively. Cool air enters through V-in near the base of the structure, is heated by solar radiation, and then rises due to convection. The warm, moisture-laden air exits through V-out, usually located near the top ends or ridge of the dryer. This passive ventilation system ensures that humidity does not accumulate excessively within the chamber, thus preventing microbial growth and condensation.

Also visible in the diagram are symbols labeled T and H, which represent temperature and humidity, respectively. These parameters are monitored at different points within the chamber to evaluate the thermal performance of the dryer and ensure that the conditions remain within optimal drying ranges for the specific crop. For pepper, efficient drying occurs between 40°C and 55°C with moderate humidity.

The greenhouse solar dryer used in this study closely followed the structure illustrated in the diagram, with several practical adjustments. The frame was constructed using aluminum for structural rigidity and was enclosed entirely with transparent glass instead of polycarbonate. This provided excellent solar transmission and contributed to a significant internal heat gain under sunny conditions.

Prior to the commencement of drying experiments, the greenhouse dryer required repairs. The glass door and parts of the aluminum frame had been damaged and needed to be refixed. Broken glass panels were replaced, and the frame joints were reinforced to prevent heat leakage. The entire unit was mounted on a metal iron sheet, painted black to improve solar absorption and minimize heat losses through the floor. This metallic base also contributed to heating through conduction.Unlike mechanically assisted dryers, the greenhouse dryer in this project did not use any fans, heaters, or solar panels. It operated entirely on natural convection and solar energy.

The performance of a greenhouse solar dryer depends on an effective combination of solar radiation trapping, controlled airflow, and moisture removal. The following thermodynamic principles govern its operation:

- Solar Radiation and Greenhouse Effect: Solar energy enters through the transparent glazing and heats up surfaces and air within the chamber. The transparent glass transmits shortwave radiation but traps longwave re-radiation, elevating the internal temperature which is the greenhouse effect. The trapped heat leads to rapid moisture evaporation from the product.
- Convection: As the internal air heats up, it becomes less dense and rises, generating an upward flow. This creates a suction effect that draws fresh, cooler air in from below (V-in) and pushes moist, warm air out through the outlet (V-out). The continuous circulation promotes consistent drying across trays.

- Conduction: Heat absorbed by metallic or solid surfaces (like tray supports or the metal base) is conducted to the produce in direct contact. This helps warm up the product evenly and supports the internal movement of moisture from the core of the pepper to the surface.
- Insulation: Although the glass provides transparency, its thickness and sealed construction also function as insulation. It reduces heat loss to the external environment, especially during wind disturbances or temperature drops. The aluminum frame which is a conductor, was minimized in contact exposure to retain internal heat.

These mechanisms collectively create a stable micro-environment that accelerates drying while maintaining the quality of the produce. In practical use, daily temperature inside the chamber was recorded as being consistently 6–12°C higher than ambient conditions, demonstrating strong thermal performance.

2.5 Working Principle of a Hybrid Solar Dryer

A hybrid solar dryer combines two or more energy sources to ensure consistent and efficient drying of agricultural produce, regardless of climatic variability. This system primarily uses solar energy, supplemented by auxiliary sources such as electric heaters, biomass burners, or photovoltaic systems which is to guarantee continuous drying even during cloudy weather or at night.In normal operation, solar radiation is collected by a solar thermal collector, typically made of a black-painted metallic plate enclosed in transparent glazing material like polycarbonate or glass. The solar energy heats up the absorber plate, which then transfers the heat to air within the collector via conduction. The hot air is either moved passively (natural convection) or actively (with a solar-powered fan) through a drying chamber where the agricultural products are arranged on trays.

As heated air passes through the drying chamber, it absorbs moisture from the wet produce through convective heat transfer. Simultaneously, the latent heat of vaporization enables moisture within the product to transition from liquid to vapor. This vapor is then carried away by the moving air stream, ensuring continuous drying. Exhaust vents are typically placed at the top of the chamber to allow moist air to escape, while drier air circulates in, keeping the drying cycle effective.

One of the key features of the hybrid solar dryer is the backup heating mechanism. When sunlight is insufficient, the system automatically activates an electric or biomass-based heater, or may continue operating with energy stored in batteries charged by photovoltaic panels. This ensures that drying conditions remain optimal throughout the day. The integration of temperature and humidity sensors helps regulate the environment within the chamber, reducing the risk of over-drying and preserving the quality of the product.

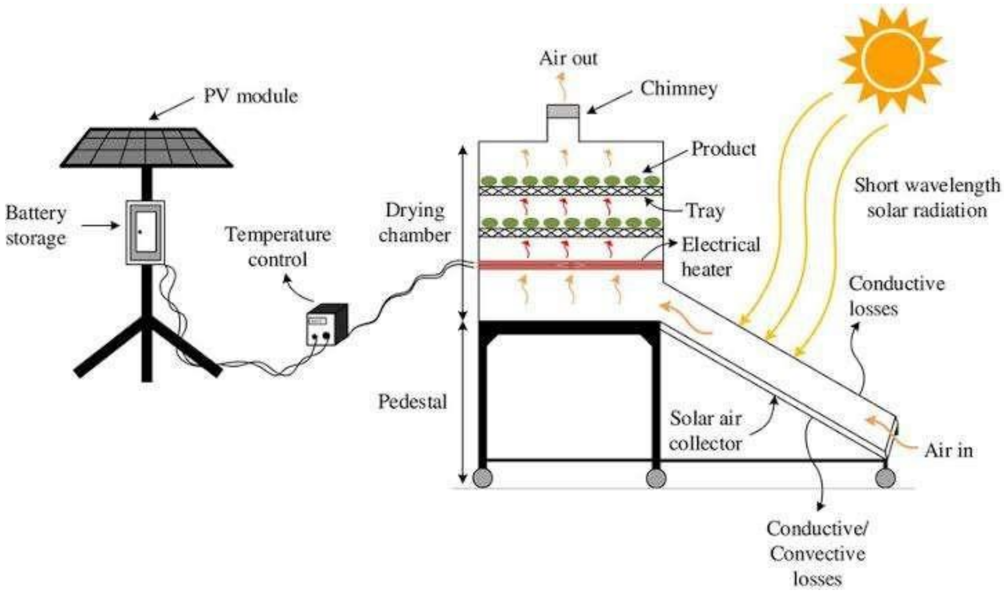


Figure 2.5.1: Working Principle of a Hybrid Solar Dryer

Hybrid dryers are especially beneficial for crops like tomatoes, peppers, and cassava, which require consistent drying conditions to prevent microbial spoilage and preserve nutritional value. Studies by Elwakeel et al. (2024) and Hossain et al. (2023) demonstrated that hybrid dryers significantly reduced drying time and improved overall efficiency compared to open sun or conventional solar drying.

2.6 Design Considerations for the Solar Dryers

The design of solar drying systems requires a careful balance between thermal performance, structural durability, material availability, and the nature of the agricultural product being dried. In this study, the design of both the indirect solar dryer and the adaptation of an existing greenhouse solar dryer were centered on practical efficiency, energy independence, and preservation quality especially for a perishable, high-moisture crop like pepper. Several technical and environmental factors were taken into account to ensure the constructed systems met these performance targets within the limitations of available resources.

A fundamental consideration was the type of drying method. The indirect solar dryer was selected for its ability to isolate the product from direct solar radiation, thereby reducing the risk of nutrient degradation, color bleaching, or contamination by dust and insects. Unlike direct sun drying, the indirect method ensures that heat is transferred through warm air generated in a separate collector unit and channeled into a drying chamber. This reduces exposure to ultraviolet radiation while still taking advantage of solar energy. On the other hand, the greenhouse solar dryer although naturally allowing direct sunlight into the chamber was retained for its passive heating advantage and enclosure benefits. Its large transparent surface and closed design promote heat buildup, providing favorable thermal conditions for drying.

The nature of the product in this case, sliced pepper played a central role in determining drying chamber volume, tray surface area, and airflow rate. Pepper contains a high level of moisture and has soft, thin-walled tissue that deteriorates quickly under poor drying conditions. As such, the chamber needed to allow adequate airflow to ensure uniform drying and prevent microbial growth. The design included space for different layers of pepper on each tray to optimize surface area exposure and minimize drying time. Trays were selected to be lightweight and non-reactive; plastic trays were used in this case, supported by a welded iron within the chamber. Their spacing was planned to allow even vertical airflow through the product layers.

The inclination of the solar collector in the indirect dryer was another thermal optimization factor. A tilt angle of approximately 30° was adopted based on the latitude of the study location in southwestern Nigeria. This angle maximizes solar irradiance throughout the day, allowing optimal sunlight penetration and energy absorption. The collector surface was covered with transparent glass (10mm inner, 5mm outer) to enable greenhouse trapping while also offering durability against weather elements. The absorber plate beneath the glass was coated in black automobile paint to maximize thermal absorption and raise the internal air temperature effectively.

Material selection was driven by a need for thermal efficiency, cost-effectiveness, and local availability. The frame of the indirect dryer was constructed using welded metal sheet to provide strength and support for both the collector and the chamber. The chamber walls and collector body were lined with fiber insulation to reduce heat losses. The outer structure was enclosed with HDF plywood board and sealed to prevent air leakage. Aluminum angle were used in vulnerable junctions especially between glass and frame to prevent water seepage during rainfall. For the greenhouse dryer, existing aluminum frames were refurbished, broken glass were replaced, and the base was restructured with a painted metalsheet to enhance absorption and structural integrity.

Airflow dynamics also informed key decisions. The indirect dryer operated without forced convection; thus, the internal design was adjusted to maximize natural air movement. The collector was positioned at a height slightly lower than the chamber to encourage warm air to rise and enter the drying space by buoyancy. The outlet above the chamber helped to maintain the pressure gradient, expelling moist air and drawing in fresh hot air from the collector. This continuous flow created the draft needed for uninterrupted moisture removal, even in the absence of a fan.

Heat retention and energy efficiency were further considered through insulation design. Fiber insulation was used in the indirect dryer to minimize conductive and convective heat loss through the chamber walls. The greenhouse dryer naturally retained heat through its enclosed glass walls, but gaps from wear and tear were sealed during repairs to improve performance. These retention measures were essential for maintaining high internal temperatures without external energy input.

The ease of assembly and repair was another practical design factor. The project was executed in a low-resource setting, and as such, the design had to accommodate local fabrication techniques and materials. The indirect dryer was constructed over the course of several days, including time spent welding the frame, cutting wooden boards, and assembling the collector. The greenhouse dryer, already available, required structural modifications and realignment to restore its functionality. By prioritizing modular components, both dryers could be dismantled or upgraded with minimal technical intervention in the future.

2.7 Material Selection and Durability in Solar Dryer Fabrication

The choice of materials for the construction of solar dryers is critical for ensuring durability, thermal efficiency, and cost-effectiveness. Materials should be selected based on their ability to withstand high temperatures, resist corrosion, and maintain thermal efficiency over time (Esper, and Muhlbauer, 1996).

- **Absorbing Surfaces**: The absorbing surfaces of the solar collector are typically coated with black paint or a selective coating that maximizes absorption and minimizes reflection of solar radiation. Studies by Ky *et al*. (2021) have shown that selective coatings can enhance the thermal efficiency of collectors by up to 15%.

- **Glazing**: Glazing materials, such as glass or transparent plastic sheets, are used to cover the solar collector and drying chamber. Glass is preferred for its high transmissivity and durability, though it is more expensive and heavier than plastic alternatives like polycarbonate or acrylic (Ismail, and Ibrahim, 2021).

- **Insulation**: The insulation of the drying chamber and collector is vital for retaining heat within the system. Materials such as fiberglass, foam, and sawdust are commonly used to reduce heat losses (Bala *et al* 2001). Proper insulation ensures the dryer operates efficiently even during periods of lower solar radiation.

CHAPTER THREE

3.0 Materials And Method

3.1 Materials

The following are the materials that were used for the consstruction of the solar dryer.

3.1.1 Direct Sun Drying System

Cassava slices were spread thinly on trays exposed directly to sunlight. The setup was simple, with no structural protection from weather or contaminants.

3.1.2 Indirect Solar Dryer

3.1.2.1 High Density Fibreboard(HDF)

The material used for the indirect solar dryer chamber is high density fibreboard(HDF). High density fibreboard (HDF) was selected for constuction part of indirect solar dryer due to its structural and thermal advantages. It it more cost-effective than hardwood or metal sheets, and is widely available in most regions, making it ideal for small-to medium-scale dryer project and provides a clean, uniform surface ideal for painting to absorb heat effetively. It can easily be cut, drilled, and shaped without splitting which makes it user friendly during construction. It has a low thermal comductivity, which minimizes heat loss from the collector and drying chamber . This improves energy efficiency and maintains a more stable internal temperature. The smooth finish of HDF makes it ideal for painting, especially black coating inside the collector that absorb solar radiation efficiently . HDF has high density and rigidity, providing structural integrity for frames, trays, and panels within the solar dryer. While not water, HDF resist swelling when properly painted or sealed. This allows it to be safely used in enclosed indirect systems, where is not directly exposed to high humidity.

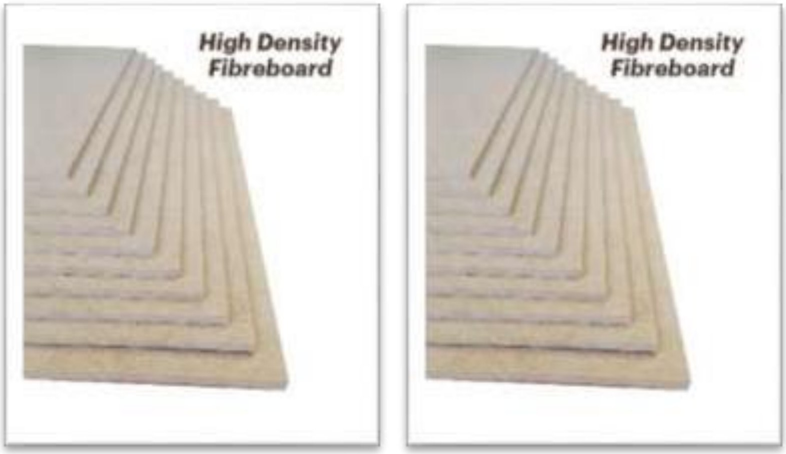
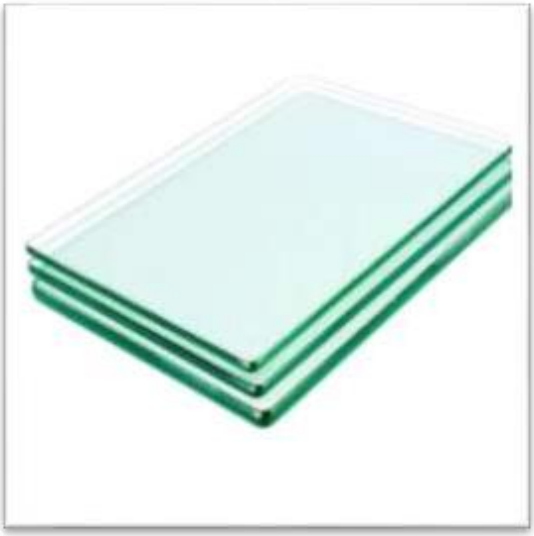


Fig.3.1.2.1: High Density Fibreboard

3.1.2.2 Transparent Cover

The requirements for the transparent cover are that it should have a low reflectance, low absorptance, and high transmittance. The material that fit this requirement is glass; it transmits a high amount of solar raditation incident on the collector and suppresses the convective and relative losses from the top of the solar collector plate. Tempered glass with low iron content was used due to it strength, safety, and higher collector efficiency. It is highly efficient amd also has a high mechanical strength compared to common glass. Tempered glass of 0.001m was used outside and tempered glass of 0.005m was used inside.

3.1.2.3 Collector Casing

High density fibreboard(HDF) was used for the collector casing; this is because it is cheap. The collector frame holds the absorber plate, and transparent cover. HDF also lasts long and helps to prevent much heat loss from the collector.

Fig.3.1.2.3: Collector Casing

3.1.2.4 Collator Casing Insulation (Fibre)

Fibre of 0.030m thickness was used to insulate the bottom and sides of the collector. The fibre was cut int the required sizes and fitted into the collector casing. It is cheap, readily available and has a good insulation properties.

Fig.3.1.2.4: Collector CasingInsulation(Fibre)

3.1.2.5 Drying Trays

Plastic trays were selected for drying because of it thermal behaviour, hygiene, durability and food safety. It does not absorb or transfer heat quickly, which prevent overheating of the drying product(e.g cassava). This is essential for in indirect dryer where uniform drying is required without heat spot. It ensures that the taste, color, and safety of the dried cassava are maintained. Plastic trays are lighter than metal or wood alternatives, making them easier to load, unload, and clean , especially important for small –scale or rural setups. Unlike metal trays, plastics trays are not prones to rust or corrosion, particularly in high humidity drying environments

Fig.3.1.2.5: Drying Trays

3.1.2.6 Supporting Frames

The supporting frame was constructed using angle iron of 0.04m and 0.02m thickness with a one and hafl inch wideness. The entire dryer was mounted on the supporting frame to sustain and maintain a better airflow.

Fig.3.1.2.6: Supporting Frames

3.1.2.7 The Absorber Plate

The absorber plate's main function is to absorb the solar radiation incident on the collector. Copper, mild steel and aluminium all have high thermal conductivity and absortivity, but iron metal sheet is selected due to it beingh lighter than mild steel and its cost being relatively lower than that of copper. It is also corrosion resistant, ductile and a good reflector of visible light and heat. Due to the lack of availability of selective coating like black chrome, plain black paint was used to coat the absorber plate to increase the amount of the incident solar radiation absorb by the plate.

Fig.3.1.2.7: The Absorber Plates

3.1.2.8 Aluminium Angle Iron

The aluminium angle iron was trategically placed at glass-metal joints to seal gaps and prevent rainwater ingress, improving weather resistance.

Fig.3.1.2.7: The Absorber Plates

3.1.2.9. Automobile Black Paint

Was applied to the absorber surface within the solar collector and to some internal components of the indirect solar dryer to enhance heat absorption. The color black was specifically chosen because of its high absorptivity, allowing it to capture and retain more solar radiation compared to lighter colors. By increasing the efficiency of thermal energy collection, the black-painted surfaces helped raise the air temperature inside the collector, thus improving the overall drying performance of the system.

Metal hinges, nails, screws, and handles were used as fastening and functional components throughout the construction of both dryers. Hinges were attached to chamber doors to allow smooth opening and closing during loading and unloading of pepper samples. Screws and nails secured the plywood panels, metal frames, and glass supports, ensuring structural firmness. Handles provided ease of access and safe operation. These materials were chosen for their mechanical strength, reusability, and resistance to wear under frequent use, all contributing to the overall durability and usability of the dryers.

3.1.3 Greenhouse

The greenhouse dryer utilized in this study was previously constructed and located within the experimental site. The materials used in the manufacture of the greenhouse dryer has some special characteristics. First, choose materials affordable to expectations in its application were able to save cost from the price. Second, lightweight materials to facilitate the operation of the device itself, for example if you want to be moved or taken to another place. Third, the selected material has the properties of heat collectors. With these properties then the heat will accumulate inside the tool so that it can speed up the drying process. This tool is also made of a material that is not easily broken, broken or porous so as to reduce the risk of damage and loss. The aluminum framework formed the structural skeleton of the greenhouse solar dryer, supporting the glass walls. Aluminum was selected due to its lightweight nature, corrosion resistance, and structural stability under prolonged exposure to sunlight and humidity. Its strength allowed it to hold the glass wall securely in place, while its resistance to rust ensured long-term durability. The use of aluminum also made it easier to assemble and repair the structure when damaged, as was done during the rehabilitation phase of the project.

3.2 Data Collection Instruments

To monitor the environmental and drying parameters during the experiment, the following instruments were employed:

- Digital Multimeter with Sensor Probe: This multifunctional device was used to measure air temperature inside each drying chamber as well as the ambient environment (see figure 3.2.1).

Figure 3.2.1 Digital Multimeter with sensory probe

- Digital Hygrometers: Used alongside the multimeter is the Hygrometer used to take humidity readings, ensuring accurate environmental monitoring. It can also be used to take readings of both temperature and time (see figure 3.2.2).

Figure 3.2.2 Digital Hygrometer

- Solar Radiation Meter (Pyranometer) Model SM206: Used to measured incident solar radiation in W/m². Accurate solar input data was essential for calculating thermal efficiency (see Figure 3.2.3).

Figure 3.2.3 Solar Radiation Meter (Pyranometer)

- Digital Weighing Scale: Used to measure weight loss of pepper samples at regular intervals to evaluate moisture reduction (see figure 3.2.4).

Figure 3.2.4Digital Weighing Scale

3.3 Construction Process

The construction process began with proper planning and preparation. We first made a clear design of how we wanted both the indirect and greenhouse solar dryers to look and work. We took accurate measurements to guide us on the size of each part and how they would be fixed together.

The metallic flat plate used for the solar collector of the indirect dryer was measured to ensure maximum absorption of solar energy. The solar collector was designed using a flat metallic plate with a length of 1.23m, breadth of 0.57m and height of 0.21m. This plate serve as the main absorber of solar radiation to heat the incoming air. The drying chamber (cabinet), where the sliced produce is to be placed, had a length of 0.85m and a breadth of 0.525m. At the top section, the chimney was tilted in case of rainfall: the chimney back measured 0.38m by 0.285m, the chimney side measured 0.205m by 0.38m and the chimney head had a length 0.28m, breadth of 0.33m and height of 0.125m. The door of the drying cabinet was also measured at 0.72m in length and 0.67m in breadth for easy access to the trays.

Figure 3.3.1 during welding process

We then moved the flat metal iron sheets meant for building the frame of the indirect solar dryer to a welding workshop. The welding was done at a location in GRA, Ilorin, behind the Governor's Office.

Figure 3.3.2 framework of the indirect solar dryer

We were directly involved in the welding process. We helped in handling the materials, checking that the correct measurements were followed, and made sure the structure was built according to our plan. After it was completed, we brought the welded frame back to the school. Before assembling it, we painted the whole metal frame with Automobile black paint. This helps it to absorb more heat from the sun. After the paint dried, we moved the frame to the top of the decking behind Physics Lab A. This high platform was chosen so that shadows would not disturb the dryers during the experiment. We used a ladder to climb up and set everything in place.

The next step was to cover the metal frame using High-Density Fibreboard (HDF) plywood. This part of the work took another few days. The wood was used to close the sides of the dryer, while glass was fixed on the top of the solar collector to allow sunlight in. We used two types of transparent glass: the inside glass was 10mm thick, and the outer one was 5 mm thick. We sealed the edges using aluminum angle, and rubber was added to prevent water from entering when it rains.

also installed hinges, handles, and locks on the door of the dryer to make it easy to open and close. Nails and screws were used to fix all parts properly, and hammers were used for nailing. After the full structure was completed, we cleaned the dryer both inside and outside.

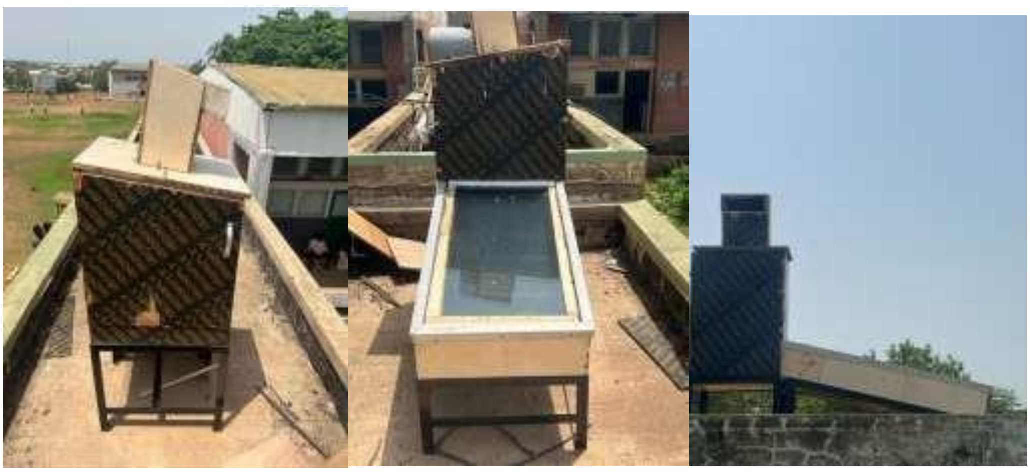


Figure 3.3.3 Complete construction of the indirect solar dryer

We also worked on the greenhouse solar dryer, which had previously been used but required significant repairs. The overall structure of the greenhouse dryer has a measurement of 1.545m in length, 1.045m in breadth and 0.10m in height. The greenhouse has a raised portion on top designed to enhance convection which also has a measurement of 0.495m in height, 0.55m in breadth and 1.04m in length. The collector plate newly welded for the greenhouse has a measurement of 1.49m in length and 1.02m in breadth.

Repairs include replacing broken glass panels and fixing the door. The entire dryer was cleaned and reassembled making it ready for the experiment.

Figure 3.3.4 Complete construction of the greenhouse solar dryer

Just like the indirect dryer, it was also mounted on the decking beside it, facing the same direction for equal sun exposure. Both dryers, the newly constructed indirect solar dryer and the repaired greenhouse dryer were now ready to be used for the drying experiment. They were placed close to each other to ensure that both received similar sunlight throughout the test period.

3.4 Experimental Setup

The experimental setup began with the preparation of our sample fresh cassava (Manihot esculenta Crantz.) used for the drying process. The cassavas was gotten from a farmer at the neighborhood in Ilorin and then brought to the laboratory for preparation. The harvested cassavas were washed with clean water to remove any surface contaminants. After washing, it was peeled, and each cassava was sliced into two halves to enhance moisture release during the drying process.

Next, plastic trays were wrapped with aluminum foil, and the weight of each empty tray (including the foil) was measured using a digital weighing scale. This initial measurement was necessary to determine the net weight of the cassava after loading. The sliced cassavas were then evenly arranged into three trays in which one was assigned to each of the drying systems: the indirect solar dryer, the greenhouse solar dryer, and the open sun drying method.

Each tray was weighed again after loading with the cassavas sliced. The actual weight of the cassava was obtained by subtracting the tray-and-foil weight from the total weight. These trays were then placed inside, all of which had been previously installed on a decking located behind Physics Laboratory A, Kwara State Polytechnic, Ilorin. The open sun drying tray was placed on a layer of nylon sheet directly on the decking to protect it from contamination.

Figure 3.4.1: Cassava in the tray placed inside Indirect Solar Dryer

Figure 3.4.2: Tray placed inside Greenhouse Solar Dryer

Figure 3.4.3: Tray placed under Open Sun Dryer

Measurements and observations were carried out hourly from 9:200am to 4:20pm, 8:10am to 4:10pm. 830am to 3:30pm, 8:00am to 4:00pm, 8:15am to 4:15pm, and 8:25am to 4:25pm daily respectively across a five-days drying period. The data collected included: Chamber temperature and humidity inside each dryer, using a digital multimeter with probe sensors and digital hygrometer.Weight of cassava samples, using a digital weighing scale, recorded to track moisture loss over time.

Each measuring instrument was calibrated daily before use to ensure accuracy. During the experiment, a sensor fault was detected in the digital multimeter, which led to unusual temperature readings. This was corrected by replacing the faulty probe and changing the batteries of both the multimeter and weighing balance to maintain consistent performance.Although data collection was interrupted for a few hours due to rainfall, observations resumed immediately when conditions stabilized. The same trays remained in their original positions throughout the experiment, and no agitation or turning of the cassavas sliced was performed, ensuring uniform exposure across all setups.

The entire setup allowed a systematic comparison between the indirect solar dryer, greenhouse solar dryer, and open sun drying method, focusing on their respective thermal efficiency for both indirect and green house drying systems, moisture removal capacity, and drying performance under real environmental conditions.

3.5 Performance Evaluation

This is the performance evaluation for evaluating the thermal performance and drying behavior of three solar drying systems: open sun drying, greenhouse solar dryer, and indirect solar dryer was designed to allow systematic data collection and accurate analysis. Hourly readings were collected for each method over multiple days. The study was conducted using cassava sample, and performance was evaluated using the following parameters:

3.5.1 Determination of Moisture Content Reduction of the sample(cassava)

As adorpted by Esper *et al* (1996). The amount of moisture removed from the products was obtained using the expression;

$$\text{Moisture Content} = \frac{M_i - M_f}{M_f} \quad \text{--- Eq.(1)}$$

Where

MC= Moisture content of the sample(cassava);

M_i= Initial mass of sample(cassava)(g);

M_f= Final mass of sample(cassava) (g).

3.5.2 Determination of Drying Rate of the sample(cassava)

As used by Chaudhari *et al* 2022. The drying rate indicates how quickly moisture is removed from the cassava sample over time. It is measured in grams per hour (g/h) or kg/h. It is calculated using the expression below;

$$\text{Drying Rate} = \frac{M_i - M_f}{T} \quad \text{---Eq.(4)}$$

Where

M_i= Initial mass of sample(cassava)(g);

M_f= Final mass of sample(cassava) (g).

t= time interval (1 hour)

A higher drying rate indicates more efficient moisture removal.

3.5.3 Determination of Thermal Efficiency

As adorpted by Deepak *et al* (2025). The drying efficiency of the dryer was obtained using the expression

$$\eta_{cdg} = \frac{MC_{pa}(T_i - T_O)}{A_c I_g} \qquad \text{---Eq.(6)}$$

Where ;

C_{pa}: $Specific\ Heat\ Capacity\ of\ Air\ (C_{pa} : 1.005\ J/g/$°C)

$M : Mass\ of\ Sample$

$T_i : Collector\ Temperature$

$T_O : Ambient\ Temperature$

$I_g : Solar\ Radiation$

$A_c : Area\ of\ the\ collector\ of\ indirect\ drying\ system(Area\ of\ Cube)$

$where\ A_c : 2(1.23 \times 0.57 + 0.57 \times 0.21 + 1.23 \times 0.21)$

$$= 2(0.7011 + 0.1197 + 0.2583) = 2(1.0791) = 2.1582 \approx 2.16m^2$$

$A_c : Area\ of\ the\ collector\ of\ greenhouse\ drying\ system(Area\ of\ rectangle)$

$where\ A_c : (l \times b) = (1.49 \times 1.02) = 1.52m^2$

3.6. Sample Calculations Using Experimental Data (Day 1 - Day 6)

Calculation of Moisture Content

Tray 2 – Open Sun Drying (DAY 1)

$$\text{Moisture Content} = \frac{M_i - M_f}{M_f}$$

Initial Weight M_i: 524g

Final Weight M_f: 256g

- Time: 11:30

$$\text{Moisture Content} = \frac{524 - 256}{256} = 1.046g$$

- Time: 12:30

$$\text{Moisture Content} = \frac{485 - 256}{256} = 0.894g$$

Tray 2 – Indirect Sun Drying (DAY 1)

$$\text{Moisture Content} = \frac{M_i - M_f}{M_f}$$

Initial Weight M_i: 660g

Final Weight M_f: 365g

- Time: 11:30

$$\text{Moisture Content} = \frac{660 - 365}{365} = 0.808g$$

- Time: 12:30

$$\text{Moisture Content} = \frac{641 - 365}{365} = 0.756g$$

Tray 2 – Greenhouse Drying (DAY 1)

$$\text{Moisture Content} = \frac{M_i - M_f}{M_f}$$

Initial Weight M_i: 641g

Final Weight M_f: 359g

- Time: 11:30

$$\text{Moisture Content} = \frac{641 - 359}{359} = 0.785g$$

- Time: 12:30

$$\text{Moisture Content} = \frac{578 - 359}{359} = 0.610g$$

Calculation of Drying Rate

Tray 2 – Open Sun Drying (DAY 1)

$$\text{Drying Rate} = \frac{M_i - M_f}{T}$$

Initial Weight M_i: 524g

Final Weight M_f: 256g

- Time: 11:00

$$\text{Drying Rate} = \frac{524 - 256}{60} = 4.46g \quad \text{Drying Rate} = \frac{524 - 256}{3600} = 0.07g$$

- Time: 12:00

$$\text{Drying Rate} = \frac{485 - 256}{60} = 3.81g \quad \text{Drying Rate} = \frac{485 - 256}{3600} = 0.063g$$

Tray 2 – Indirect Solar Drying (DAY 1)

$$\text{Drying Rate} = \frac{M_i - M_f}{T}$$

Initial Weight M_i: 660g

Final Weight M_f: 365g

- Time: 11:00

$$\text{Drying Rate} = \frac{660 - 365}{60} = 4.916g \quad \text{Drying Rate} = \frac{660 - 365}{3600} = 0.0819g$$

- Time: 12:00

$$\text{Drying Rate} = \frac{641 - 365}{60} = 4.6g \quad \text{Drying Rate} = \frac{641 - 365}{3600} = 0.076g$$

Tray 2 – Greenhouse Drying (DAY 1)

$$\text{Drying Rate} = \frac{M_i - M_f}{T}$$

Initial Weight M_i: 641g

Final Weight M_f: 359g

- Time: 11:00

$$\text{Drying Rate} = \frac{641 - 359}{60} = 4.7g \quad \text{Drying Rate} = \frac{641 - 359}{3600} = 0.078g$$

- Time: 12:00

$$\text{Drying Rate} = \frac{578 - 359}{60} = 3.65g \quad \text{Drying Rate} = \frac{578 - 359}{3600} = 0.060g$$

Calculation of Efficiency

Tray 2 – Indirect Solar Dryer (DAY 1)

$$\eta_{cdg} = \frac{MC_{pa}(T_i - T_O)}{A_c I_g}$$

C_{pa}: *Specific Heat Capacity of Air*

where C_{pa} : $1.005\ J/g/^{\circ}\mathrm{C}$

M : *Mass of Sample*

T_i : *Collector Temperature*

T_O : *Ambient Temperature*

I_g : *Solar Radiation*

A_c : *Area of the collector (Area of Cube)*

where A_c : $2(1.23 \times 0.57 + 0.57 \times 0.21 + 1.23 \times 0.21) = 2(0.7011 + 0.1197 + 0.2583) = 2(1.0791) = 2.1582 \approx 2.16m^2$

- Time: 11:00

$$\eta_{cdg} = \frac{MC_{pa}(T_i - T_O)}{A_c I_g} = \frac{660 \times 1.005\ (34.0 - 25.2)}{2.16 \times 448} = \frac{5837.04}{967.68} = 6.032$$

- Time: 12:00

$$\eta_{cdg} = \frac{MC_{pa}(T_i - T_O)}{A_c I_g} = \frac{641 \times 1.005\ (46.5 - 32.3)}{2.16 \times\ 634} = \frac{9147.711}{1369.44} = 6.680$$

Tray 2 – Greenhouse Dryer (DAY 1)

$$\eta_{cdg} = \frac{MC_{pa}(T_i - T_O)}{A_c I_g}$$

C_{pa}: *Specific Heat Capacity of Air*

where C_{pa} : $1.005\ J/g/$°C

M : *Mass of Sample*

T_i : *Collector Temperature*

T_O : *Ambient Temperature*

I_g : *Solar Radiation*

A_c : *Area of the collector (Area of Cube)*

where A_c : $(l \times b) = (1.49 \times 1.02) = 1.52 m^2$

- Time: 9:30am

$$\eta_{cdg} = \frac{MC_{pa}(T_i - T_O)}{A_c I_g} = \frac{641 \times 1.005\ (26.0 - 25.2)}{1.52 \times 448} = \frac{515.364}{680.96} = 0.76$$

- Time: 10:30am

$$\eta_{cdg} = \frac{MC_{pa}(T_i - T_O)}{A_c I_g} = \frac{578 \times 1.005\ (39.4 - 32.3)}{1.52 \times 634} = \frac{4124.319}{963.68} = 4.28$$

CHAPTER FOUR

4.0 RESULT AND DISCUSSION

The effectiveness of various solar drying systems in dehydrating sliced cassava was evaluated through a series of experimental tests. This study specifically aimed to identify the most efficient drying method while also highlighting the unique advantages of each drying system employed. Over the course of four days, 660g of cassavas were reduced to 374g using an indirect solar dryer. In comparison, a greenhouse solar dryer effectively reduced 671g of cassava to 361g, while open-air drying decreased 524g of cassava to 284g. The measured parameters included (a) solar radiation incident on the solar collector, (b) ambient temperature, (c) chamber temperatures of both the indirect and greenhouse solar dryers, (d) collector temperature in the indirect solar dryer, (e) humidity levels, (f) moisture content of dried mass, and the overall drying rate. The performance testing adhered to international standards set forth by ASABE/ASAE (2007) for solar air collectors. Temperature measurements at various points within the collector and chambers of the dryers were conducted using a K-type thermocouple multimeter. The drying regimen commenced daily at 8:00 AM and concluded by 4:00 PM.

CHAPTER FIVE

5.0 Conclusion

A comparative thermal performance analysis of three distinct drying systems greenhouse drying, indirect solar drying, and traditional open sun drying was successfully conducted. The results demonstrate that the greenhouse dryer achieved the highest average drying temperature and the most rapid drying rate. The indirect solar dryer followed closely, while open sun drying, despite being the most accessible and cost-effective, exhibited the slowest drying rate and was notably vulnerable to environmental contamination and fluctuations in weather conditions

The greenhouse solar dryer proved to be the most effective among the three, offering faster drying, better temperature regulation, and greater protection against environmental elements. The indirect solar dryer also performed well, particularly in thermal control and hygiene. However, the direct sun drying method, while cost-free, remains the least reliable due to exposure to weather changes, pests, and inconsistent drying rates

The findings confirm that both the greenhouse and indirect solar dryers offer superior thermal efficiency, enhanced product quality, and significantly reduced drying time when compared to conventional open sun drying methods.

5.1 Recommendation

It is recommended that small- and medium-scale farmers adopt greenhouse or indirect solar drying systems, as these technologies offer improved drying efficiency and better hygiene standards for agricultural products.

Furthermore, governmental bodies and agricultural development agencies are encouraged to promote the adoption of solar drying technologies by offering subsidies, capacity-building programs, and awareness campaigns. These initiatives can play a vital role in reducing post-harvest losses and strengthening food security

Finally, future research on drying systems should prioritize the development and evaluation of hybrid drying technologies that integrate solar energy with auxiliary heating sources. Such innovations would ensure consistent drying performance during periods of low solar intensity or nighttime operation

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