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

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CERTIFICATION

This is to certify that this project work has been written by **GROUP THREE** with matric numbers **HND/23/SLT/FT/0828, HND/23/SLT/FT/0064, HND/23/SLT/FT/0013, HND/23/SLT/FT/0546, HND/23/SLT/FT/0366, HND/23/SLT/FT/0190,** 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 our academic pursuit. All Glory to God and our Supervisor (**Dr. Olaore K.O.**) also to our parent, and friends who has never failed to give us financial and moral support for all our needs during the time we developed our systems and for teaching us that even the largest task can be accomplished if it is done one step as a time.

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May God bless and keep you all (amen).

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

In recent years, the intersection of agricultural sustainability and renewable energy application has become a critical area of investigation, particularly in regions where post-harvest losses continue to undermine food security and economic resilience. Among the major horticultural crops grown across the region, tomatoes (Solanum lycopersicum) hold significant nutritional and economic importance. However, their high water content and delicate skin structure render them highly susceptible to rapid post-harvest spoilage under ambient tropical conditions. According to Olumekun and Akinoso (2017), post-harvest losses in tomatoes in Nigeria are estimated at over 40%, largely due to inadequate preservation and transportation infrastructure. These losses represent not only a threat to food supply but also a financial setback for smallholder farmers and local vendors who depend on seasonal harvests for income generation.

Traditional preservation methods such as open sun drying are still widely used, especially in rural and semi-urban communities. While sun drying offers zero operational costs and minimal technical barriers, it poses several disadvantages including contamination by dust and insects, uneven drying, dependence on clear weather, and vulnerability to spoilage from sudden rainfalls or nocturnal moisture absorption (Bala & Mondol, 2019). These challenges have sparked a growing interest in solar drying systems, which offer enhanced environmental control while harnessing renewable energy to dry crops more efficiently.

Solar dryers are engineered systems designed to absorb solar radiation and convert it into thermal energy for the purpose of controlled dehydration. Unlike traditional sun drying, solar dryers can protect crops from contamination and accelerate moisture removal, resulting in better preservation of color, nutrients, texture, and overall product quality (Motevali et al., 2021). The application of solar energy in food preservation aligns with global efforts to promote renewable energy use in agriculture and reduce post-harvest losses, particularly in regions with high solar radiation potential.

Three main types of solar dryers have emerged in both research and practical deployment: direct solar dryers, indirect solar dryers, and greenhouse solar dryers. Each of these configurations has unique advantages and design limitations. In a direct solar dryer, the product is placed inside an enclosed chamber covered with transparent material that allows solar radiation to enter and heat the product directly. While this setup facilitates rapid heating and drying, it may result in photodegradation of heat-sensitive nutrients due to direct exposure to ultraviolet rays (Ekechukwu & Norton, 2019). Indirect solar dryers overcome this limitation by using a separate solar collector to heat air, which is then channeled into a drying chamber where the crop is placed. This indirect heating process ensures better product quality by minimizing exposure to harmful rays and reducing surface hardening (Hossain & Bala, 2007). Greenhouse dryers combine features of both systems by enclosing the entire drying space in a greenhouse structure, which can maintain higher internal temperatures through the greenhouse effect while offering protection from external environmental factors (Ongen et al., 2020).

Open sun drying, considered the most rudimentary form of direct drying, has been used for centuries across tropical and subtropical regions. In this method, tomatoes are spread out under the open sky and exposed to direct sunlight. While the process requires no technological input, it is fraught with inefficiencies. Research by Adesina and Onwuka (2020) revealed that open sun drying is highly weather-dependent, unhygienic, and yields inconsistent moisture removal, often resulting in microbial contamination and nutrient degradation. These challenges have led to the development of more controlled alternatives like indirect and greenhouse solar drying systems, which provide better thermal regulation and protection against environmental hazards.

In indirect solar dryers, thermal energy is first absorbed by a collector unit, which heats up ambient air. This hot air is then circulated either naturally or by forced convection into a separate drying chamber containing the crop. This design isolates the drying material from direct solar radiation, reducing the risk of UV degradation and excessive surface drying. A study by Abano and Amoah (2019) comparing tomato drying in indirect and open sun methods showed that indirect dryers preserved better color, taste, and vitamin C content, and reduced the microbial load significantly. Similarly, greenhouse dryers utilize the greenhouse effect to trap solar energy within an enclosed structure, enabling the drying process to continue even under low ambient radiation. According to Ayyappan and Mayilsamy (2021), greenhouse dryers exhibit enhanced drying rates and reduced product losses, especially during partially cloudy or windy conditions.

The thermal efficiency of any solar drying system is determined not only by its peak internal temperature but also by its ability to maintain stable drying conditions over time. Rapid fluctuations in chamber temperature or air velocity can lead to inconsistent drying, case hardening, or prolonged drying periods. Therefore, monitoring and analyzing real-time temperature, humidity, and airflow within these systems is essential for performance optimization. As Muthukumar and Venkatachalam (2020) observed in their thermal performance evaluation of solar dryers, fluctuations in drying conditions lead to non-uniform product quality, necessitating design improvements in airflow control and insulation.

Tomatoes, due to their high water activity and delicate cellular structure, require a drying environment that is both efficient and gentle. High temperatures may accelerate drying but can also result in nutrient loss, color degradation, and textural damage. Conversely, excessively slow drying may promote microbial activity and lead to fermentation or spoilage. Studies by Akpinar and Bicer (2020) emphasized that the ideal tomato drying system must maintain a drying temperature between 50°C and 65°C, ensuring sufficient moisture removal while preserving nutritional and sensory attributes. This balance is often difficult to achieve with open sun drying but can be more consistently managed in indirect and greenhouse systems, provided that proper thermal regulation mechanisms are employed.

Furthermore, crop-specific research is essential because the drying behavior of tomatoes differs significantly from other agricultural produce. Their high acidity, thin skins, and uneven internal moisture distribution make them particularly challenging to dry uniformly. Comparative studies, such as the one conducted by Ismail et al. (2018), showed that even slight modifications in air velocity or drying temperature can drastically affect the drying time and final quality of tomato slices. Therefore, it is insufficient to generalize the performance of solar dryers based on other crops. A focused experimental analysis tailored to tomato drying is necessary to generate valid, crop-specific performance metrics.

In the context of increasing climate variability and global emphasis on sustainable food systems, solar drying technologies present an opportunity to reduce dependency on fossil fuels and mitigate post-harvest food loss. The integration of solar dryers into rural agricultural systems offers not only environmental benefits but also economic and social advantages. Solar dryers operate without external power inputs, making them suitable for off-grid or energy-poor regions, while also reducing long-term operational costs compared to fuel-based drying alternatives. A study by Kumar and Tiwari (2022) emphasized that properly designed solar dryers can reduce drying time by more than 40% compared to open sun drying, with significant gains in product hygiene and market value.

Despite these potential advantages, adoption of solar drying systems remains limited, often due to a lack of accessible, comparative data on their performance. Many existing designs are not optimized for specific crops or regional climatic conditions, and users are often uncertain about the trade-offs between cost, complexity, and efficiency. According to Khoshtaghaza et al. (2019), farmers are more likely to adopt solar drying technologies when performance metrics such as drying rate, thermal efficiency, and product quality are demonstrated through real-time field experiments rather than simulations or generalized models. This highlights the need for localized, data-driven evaluations that account for material properties, meteorological variation, and economic feasibility.

Furthermore, this project provides a valuable educational platform within the field of Physics and Electronics. Designing and analyzing solar dryers helps to engage students with practical applications of thermodynamics, heat transfer, fluid dynamics, and sensor-based instrumentation. Integrating measurement tools for monitoring solar radiation, chamber temperature, and product weight during drying encourages a hands-on understanding of experimental physics and engineering design. As pointed out by Adeyanju and Bolaji (2020), such experimental projects foster critical thinking, problem-solving, and innovation of all essential skills in modern applied physics curricula.

The selection of tomatoes as the target crop further underscores the relevance of this study. Tomatoes are not only one of the most consumed vegetables globally but are also particularly sensitive to drying conditions. Their perishability, combined with widespread cultivation in Nigeria and other tropical countries, makes them a strategic focus for post-harvest technology development. By evaluating and comparing open sun, indirect, and greenhouse drying methods under the same environmental conditions, this research aims to identify which design offers the most efficient, cost-effective, and quality-preserving method for drying tomatoes.

The results will provide stakeholders including researchers, farmers, extension workers, and policy-makers with actionable insights to guide the adoption, improvement, and dissemination of solar drying technologies suited to tomato processing in regions with similar climatic and socioeconomic conditions.

1.2 Statement of the Problem

Tomato production plays a vital role in the agricultural economy of Nigeria and many developing nations, but its preservation remains a significant post-harvest challenge due to its high perishability and water content. It has been estimated that up to 45% of harvested tomatoes are lost before they reach the consumer, primarily due to inadequate preservation and inefficient post-harvest technologies (Olumekun & Akinoso, 2017). Open sun drying is the most accessible traditional method still widely used, but it is prone to contamination, weather disruption, and inconsistency in drying rates, often resulting in poor-quality dried products and significant economic losses (Adesina & Onwuka, 2020).

In response, various solar drying technologies have emerged, offering better environmental control and improved drying efficiency. However, these systems differ in their design, thermal behavior, and operational performance. Despite numerous innovations, there remains a lack of rigorous comparative studies that experimentally evaluate how direct (open sun), indirect, and greenhouse solar dryers perform under the same environmental conditions, especially when drying tomatoes. Most research focuses on individual dryer types, often under controlled laboratory settings, failing to reflect real field conditions (Kumar & Tiwari, 2022; Motevali et al., 2021).

This knowledge gap complicates the selection of the most efficient and appropriate drying method for specific crops and climates. Without a practical, side-by-side thermal analysis of solar dryers, local farmers and processors lack the data needed to make informed decisions about adopting low-cost, high-performance drying technologies. Consequently, there is a pressing need for a comparative thermal performance study that considers chamber temperature behavior, drying rate, and moisture loss during tomato dehydration, thereby providing reliable data for improved dryer selection, design, and usage in real-world agricultural contexts.

1.3 Aim of 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 tomato.

1.4 Objective 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 performances of the direct and indirect solar dryers by taking hourly measurement of the temperature in the chamber of the dryers.
- To take hourly measurement of the solar radiation
- To calculate the drying rate of the direct and indirect solar dryers through hourly measurement of the weight of the tomatoes.
- To carry out a comparative study of the thermal performance of the direct and indirect solar dryers.

1.4 Scope of the Study

This study is primarily focused on the design, construction, and comparative thermal analysis of three different tomato drying systems: direct sun drying (open sun), indirect solar drying, and greenhouse solar drying. It is limited to the drying of fresh tomato slices under naturally available solar radiation in a specific geographic location within Nigeria, characterized by tropical climatic conditions.

The research involves the fabrication of a direct solar dryer and an indirect solar dryer, while the greenhouse solar dryer is based on an already existing structure. Performance data were collected through hourly measurements of drying chamber temperatures, solar radiation intensity, and the moisture loss of tomato samples across each drying method.

The study is strictly confined to thermal performance evaluation, and does not include microbiological, economic, or long-term storage analysis. The scope also excludes computer simulations or modeling techniques, instead relying entirely on field-based experimental methods. The findings are intended to offer practical, evidence-based insights for small-scale farmers, food processors, and agricultural engineers seeking sustainable tomato drying solutions adapted to local environmental and economic conditions.

1.5 Justification of the Study

The justification for this study arises from the urgent need to reduce the high post-harvest losses of tomatoes in Nigeria and similar developing regions, where preservation methods are often inefficient or absent. Given that tomatoes are highly perishable and contain over 90% moisture, their spoilage rate is particularly high under ambient storage conditions (Olumekun & Akinoso, 2017). Open sun drying, the most common traditional method, exposes the produce to dust, pests, uneven heating, and weather variations, often leading to poor quality and contamination (Adesina & Onwuka, 2020).

By constructing and evaluating both indirect and greenhouse solar dryers in comparison with direct sun drying, this study provides a data-driven understanding of their thermal performance, specifically in terms of drying temperature, drying rate, and moisture loss. Such comparative analysis is necessary to recommend the most appropriate, cost-effective, and sustainable drying technology for local tomato farmers.

Additionally, this research serves academic relevance by integrating principles of thermodynamics, heat transfer, and instrumentation into real-world agricultural applications. As emphasized by Adeyanju and Bolaji (2020), experimental projects like solar dryer development foster applied physics learning while addressing community-level challenges. Thus, this study is justified both for its scientific merit and its socioeconomic potential to enhance food security through sustainable post-harvest practices.

CHAPTER TWO

LITERATURE REVIEW

At Modibbo Adama University of Technology, Yola, Hussein et al. (2017) constructed and tested a hybrid photovoltaic (PV) solar dryer. Their system integrated PV panels, a battery storage unit, and a solar collector, allowing operations under direct sunlight and during cloudy conditions using stored energy. In drying tomato slices, their hybrid system achieved a maximum temperature of 62°C and reduced moisture content from 94.2% to 10% within six hours, compared to nine hours in a non-hybrid dryer. The drying rate and efficiency were reported as 0.08 kg/h and 71%, respectively. The authors concluded that such systems are well-suited for remote, off-grid areas with limited electricity access.

Adejumo et al. (2023) designed and evaluated a hybrid solar dryer for processing cassava grates, integrating a solar collector, drying chamber, chimney, blower unit (with heater and fan), a solar panel, and a 12V DC battery. The study was carried out to assess the influence of drying temperature and cassava variety (TMS96/1414, TMS92/0326, and TMS01/1368) on moisture loss, drying rate, and efficiency. They reported that the dryer reached maximum drying chamber temperatures of 55°C for hybrid mode and 45°C for solar mode, where both are significantly higher than the ambient 26°C. Hybrid drying reduced the moisture content from 65% to approximately 10.19% in 7 hours, while solar drying required 13 hours to reach 11%, and open sun drying took 35 hours to achieve 13%. The researchers found that TMS92/0326 exhibited the highest moisture loss (6.20 kg/kg) and drying efficiency (up to 79.71%). Drying rates across the methods were 0.899 kg/hr (open sun), 0.870 kg/hr (solar), and 0.807 kg/hr (hybrid). They concluded that drying temperature, airflow rate, and cassava variety had significant effects on performance, with the hybrid solar dryer proving most efficient in achieving rapid and uniform drying of cassava grates.

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.

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.

Singh and Gaur (2021) developed a hybrid active greenhouse solar dryer integrated with an evacuated tube solar collector, specifically targeting the drying of high-moisture agricultural products such as tomatoes. They stated that the system included a heat exchanger where hot water heated by the solar collector is circulated through copper tubes, transferring heat to the surrounding air via convection and conduction. This setup produced higher internal chamber temperatures and enhanced the moisture removal rate. Tomato slices were dried from an initial moisture content of 94.6% (wet basis) to 10% within 10 hours. The authors estimated that the dryer could yield 261 kg of dried tomato annually, with an economic payback period of just 1.73 years. Furthermore, they calculated that over a projected lifespan of 30 years, the system would mitigate approximately 169.10 tonnes of CO_2, demonstrating both environmental sustainability and cost-effectiveness. They concluded that such a system is suitable for rural agricultural processing and is well-aligned with the principles of sustainable development.

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/m², with collector flux absorption at 103 W/m². 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 24.7for 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.

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 m², 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.

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.

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.

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.

Samykano et al. (2023) investigated the performance of a single-basin, double-slope solar dryer utilizing natural convection for drying bottle gourds and tomatoes. The study aimed to present a sustainable, low-energy alternative to traditional open-sun drying, which is increasingly challenged by contamination risks and inconsistent weather conditions. The authors reported that their solar dryer achieved moisture reductions of 94.42% in tomatoes and 83.87% in bottle gourds, far outperforming open-sun drying. Drying air and plate temperatures reached 54.42°C and 63.38°C, respectively. Energy and energy efficiencies peaked at 68.5% for tomatoes and 61.78% for bottle gourds. The activation energy required for drying was significantly lower using the solar dryer: 29.14–46.41 kJ/mol for bottle gourds and 27.16–55.42 kJ/mol for tomatoes. The moisture diffusivity also showed substantial improvement, ranging between 3.12×10^{11} to 4.31×10^{11} m^2/s for bottle gourds and 2.31×10^{11} to 4.65×10^{11} m^2/s for tomatoes. An economic analysis indicated payback periods of 2 years for bottle gourds and 1.6 years for tomatoes. The researchers concluded that their system enhanced drying efficiency, preserved product quality, and aligned with sustainable post-harvest food processing goals.

Suherman et al. (2023) assessed the performance of a hybrid solar dryer for drying red chili pepper, comparing its efficiency to traditional sun drying and standard solar drying methods. The study independently tested drying air temperatures of 40°C, 50°C, 60°C, 70°C, and 80°C, evaluating temperature profiles, thermal efficiency, drying rate, energy behavior, and quality attributes such as color, vitamin C, and β-carotene content. The authors observed that the drying rate decreased with increasing temperature, while thermal chamber efficiency and drying effectiveness were inversely proportional to drying duration. The solar collector showed peak efficiency at 40°C, whereas energy and energy indicators increased with temperature. They confirmed that the hybrid dryer reduced moisture content to below 10.78%, meeting national standards. At 80°C, the dried chili retained desirable color values (L = 30.37, a = 27.45, b = 10.63), along with vitamin C content of 14.79 g/100 g and β-carotene content of 4.43 mg/100 g. The authors concluded that the hybrid solar drying method offered superior energy utilization, product quality, and thermal performance, making it an effective and sustainable option for chili drying.

King'ori and Simate (2024) investigated the drying performance and economic feasibility of a greenhouse solar dryer for small-scale tomato processing, comparing it with traditional open sun drying methods. The dryer system consisted of a steel frame structure, greenhouse-grade plastic covering, and a concrete floor. The authors conducted drying trials under natural weather conditions, with temperature and relative humidity monitored to assess their influence on drying efficiency. They reported that the greenhouse dryer achieved higher internal temperatures of 38.4°C on the first day and 45.5°C on the second day which facilitated a rapid moisture reduction to 14.9% (wet basis) within 11 hours. In contrast, open sun drying yielded only a reduction to 37.9% moisture under the same conditions, demonstrating the superior thermal performance of the greenhouse system. An economic analysis revealed a payback period of 1.6 years, indicating its investment attractiveness for smallholder farmers. The authors concluded that greenhouse solar drying technologies offer not only faster and more controlled drying but also financial viability, making them a promising strategy for value-added tomato processing in rural agricultural communities.

Yahya (2016) designed and evaluated the performance of a solar-assisted heat pump dryer integrated with a biomass furnace for drying red chillies, and assessed its drying kinetics. The study involved drying 22 kg of fresh red chillies, initially at a moisture content of 4.26 db, down to 0.08 db within 11 hours of operation. In contrast, open sun drying required 62 hours to reach comparable moisture levels, demonstrating an 82% reduction in drying time. The hybrid drying system maintained an average chamber temperature of 70.5°C, relative humidity of 10.1%, and air mass flow rate of 0.124 kg/s. The average drying rate, specific moisture extraction rate, and thermal efficiency were reported as 1.57 kg/h, 0.14 kg/kWh, and 9.03%, respectively. The study further evaluated three drying models of Newton, Henderson–Pabis, and Page to describe the drying kinetics, concluding that the Page model offered the best predictive accuracy, based on statistical metrics such as coefficient of determination (R^2), mean bias error (MBE), and root mean square error (RMSE). The author concluded that the solar-assisted hybrid dryer provided substantial time savings and consistent drying performance, and could serve as a reliable alternative to conventional sun drying.

Koua et al. (2017) experimentally investigated the thermal performance of an indirect forced convection solar dryer designed for drying cocoa beans. The system was composed of a solar collector, drying chamber, two fans, and an integrated photovoltaic power supply with battery storage. The researchers conducted experiments under three distinct meteorological conditions: sunny, partially cloudy, and cloudy. They observed that the temperature rise of the air inside the solar collector was 22.1°C on sunny days, 15.6°C on partially cloudy days, and 13.2°C on cloudy days, compared to the ambient temperature. The average solar radiation on the collector surface was measured as 644 W/m², 448 W/m², and 341 W/m², respectively. The thermal efficiency of the solar collector ranged between 34.89% and 43.40%, regardless of weather conditions, while the overall thermal drying efficiency of the system varied between 14.48% and 20.17%. They also reported that the temperature inside the drying chamber consistently exceeded ambient levels, demonstrating effective heat retention. The authors concluded that the dryer, supported by PV-powered airflow and battery storage, performed reliably across diverse weather conditions and offered a viable solution for efficient cocoa bean drying in tropical regions.Olatunbosun (2011) reported that the limitations associated with traditional open sun drying, including pest infestation, contamination, and poor hygiene, can be effectively addressed through the use of solar dryers. In his study on a domestic passive solar dryer constructed in Abeokuta, he developed a unit composed of a solar collector and a drying chamber fitted with three mesh trays. The dryer, constructed from locally available materials such as wood and polyurethane glass, achieved an internal temperature of 60.5°C—approximately 26°C higher than ambient conditions. He observed that moisture removal was significantly improved over conventional methods; for instance, cassava slices lost 199.9g of water in the solar dryer, compared to 156.8g using open sun drying. He concluded that passive solar drying provides a more hygienic and efficient alternative.

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.

In a study conducted in Kainji, Nigeria, Ogundana et al. (2022) designed and evaluated a solar dryer tailored to local meteorological conditions. Their dryer achieved an internal temperature of 74.5°C and demonstrated substantial improvements in drying efficiency over traditional methods. The study emphasized the importance of utilizing materials such as polyurethane glass and aluminum sheets to optimize thermal performance.

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.

Okeyode and Okuyelu (2023) evaluated a multifunctional electric-solar hybrid dryer used for drying cassava and red pepper. The dryer achieved moisture reductions of more than 84% and drying rates of up to 41.43 kg/hr at a drying temperature of 65°C. They reported a fabrication cost of only $260, making it affordable for small-scale farmers. The study concluded that such hybrid dryers are practical and cost-effective solutions.

Suherman et al. (2018) analyzed the drying efficiency of a solar tray dryer designed for cassava starch. Their experiments demonstrated a reduction in moisture content from 50% to 8% within a relatively short period. Internal dryer temperatures reached 60°C, while relative humidity dropped to 30%. The dryer achieved a thermal efficiency of 40%, reflecting its capacity to maintain a controlled drying environment.

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.

Silayo et al. (2015) examined cassava drying performance on various raised platforms. Their results showed that wire mesh surfaces yielded the best drying performance, significantly reducing drying time across different bed depths. The authors concluded that optimizing the surface material and bed depth could improve efficiency even in open drying scenarios.

Koleleni (2025) investigated the viability of passive solar dryers in food preservation. The dryer, constructed from wood and mild steel, reached internal temperatures over 75°C. It demonstrated drying rates nearly three times faster than open sun drying and maintained effective drying throughout the day. The study concluded that passive solar dryers are particularly advantageous for low-income communities with limited access to electricity.

Famurewa and Emuekele (2014) employed a fluidized bed dryer to study cassava drying under various air velocities and temperatures. Their statistical analysis showed that the Modified Henderson and Pabis model accurately described the drying kinetics of the cassava varieties tested. They concluded that fluidized bed drying provides a reliable basis for future dryer designs.

Hossain et al. (2023) developed a hybrid solar dryer combining a flat-plate concentrating collector, heat storage, and auxiliary heating for drying tomatoes. The dryer reduced 20 kg of fresh tomato halves to 4 kg of dried product, with efficiencies between 17–29%. Sodium metabisulphite (8g/L) pre-treatment inhibited microbial growth at temperatures below 45°C, though higher temperatures offered better color and nutrient retention. While minor losses of ascorbic acid, lycopene, and flavonoids were recorded, these were less than those in commercially dried tomatoes.

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.

In Zimbabwe, Kagande et al. (2012) designed a solar tunnel dryer that reduced tomato moisture content from 94.09% to 20.50% (dry basis) within 15 hours at air temperatures ranging between 32.6–56°C. Their findings showed that this US $500 system was cost-effective for smallholder farmers, producing high-quality dried tomatoes with minimal microbial contamination. The study emphasized the importance of temperature and airflow control, highlighting that solar tunnel dryers outperform open sun drying. They also stressed the need for rehydration to restore texture and recommended further investigation into nutritional losses due to different drying methods.

Chouikhi and Amer (2023) evaluated an indirect-mode forced convection solar dryer equipped with a photovoltaic/thermal (PV/T) air collector for tomato slice drying. The system simultaneously produced electricity and heated air. Computational fluid dynamics (CFD) validation showed a temperature variation of approximately 1°C in the collector and 2°C in the drying chamber. The average daily efficiencies recorded were 30.9% for the collector, 15.2% for the dryer, and 8.7% for the PV panel. The authors recommended 3D CFD modeling and prototype improvements for greater efficiency, and suggested future inclusion of mass transfer analysis.

Elshawadfy Elwakeel et al. (2024) assessed a tracking indirect solar dryer powered by photovoltaic cells. The study investigated drying kinetics at varying slice thicknesses (4–8 mm) and air speeds (1–2 m/s). Thicker slices extended drying time by up to 1.667 times. The tracking collector motion (TCM) outperformed fixed collector motion (FCM) in terms of higher internal temperatures and moisture diffusivity (9.30×10^{-10} m^2/s vs. 7.15×10^{-10} m^2/s). The modified Two-Term II model best described the kinetics with R^2 values of up to 0.99976. The system was also environmentally impactful, mitigating up to 6,795.4 tons of CO_2.

Vitouley et al. (2025) developed a forced-convection solar dryer for the 'Akikon' tomato variety in Benin. The drying time was halved from 1,266 to 672 minutes at temperatures between 55–70°C. While the system produced brightly dried tomatoes, color changes appeared after 7–8 months, indicating a need for improved packaging. The study recommended evaluating rehydration ability and shelf life for commercial application.

Hossain et al. (2023) developed a hybrid solar dryer combining a flat-plate concentrating collector, heat storage, and auxiliary heating for drying tomatoes. The dryer reduced 20 kg of fresh tomato halves to 4 kg of dried product, with efficiencies between 17–29%. Sodium metabisulphite (8g/L) pre-treatment inhibited microbial growth at temperatures below 45°C, though higher temperatures offered better color and nutrient retention. While minor losses of ascorbic acid, lycopene, and flavonoids were recorded, these were less than those in commercially dried tomatoes.

Aigbede et al. (2025) reviewed over 100 mathematical models for solar drying, identifying a gap in pineapple-specific models in Cotonou, Benin. Models such as Page and Wang and Singh were found most applicable for tomato drying. The study emphasized the need for localized models that optimize solar drying and minimize post-harvest losses. It also proposed a new heat balance model specifically adapted for indirect solar dryers.

Kulanthaisami et al. (2010) compared a solar cabinet dryer with open sun drying for tomato slices (4–8 mm) in Montreal, Canada. The cabinet dryer reduced moisture content from 94% to 11.5% in 300–570 minutes, compared to 435–735 minutes under OSD. The Page model best fit the drying behavior. Moisture diffusivity in the solar dryer ranged from 4.25×10^{-7} to 7.67×10^{-7} m^2/s, significantly higher than that in OSD. Solar-dried tomatoes had better color retention, rehydration ratio, and ascorbic acid levels.

Balogun et al. (2017) tested a double-compartment solar dryer in Nigeria, reducing tomato moisture from 90% to around 10.7% in two days, while OSD achieved only 25–42.9% in the same time. The solar dryer reached 58°C and an efficiency of 87.8%. The authors highlighted the dryer's capacity to protect tomatoes from contamination and environmental factors.

El-Mesery and Mao (2023) investigated infrared drying kinetics for tomato slices. Using radiation intensities of 0.14–0.35 W/cm² and air velocities of 0.5–1.5 m/s, they observed that higher radiation reduced drying time, while increased air velocity prolonged it. The Midilli model best described the drying behavior. Although infrared drying allowed for rapid moisture removal, its effects on nutritional content require further research.

2.1Working Principles of Indirect Solar Dryers

The indirect solar dryer functions through the principle of transferring heat generated by solar energy to the drying chamber without direct exposure of the crops to sunlight. In this system, solar radiation is first absorbed by a flat-plate solar collector, which is usually made of black-painted metal or absorber materials with high thermal conductivity. This collector heats the incoming ambient air, which is then directed into the drying chamber where the agricultural produce is placed on drying trays. The system is designed to ensure that heat transfer occurs efficiently through the mechanisms of conduction, convection, and radiation, all while minimizing heat losses through effective insulation and maximizing air exchange through inlet and outlet vents.

- Conduction: This in the indirect solar dryer occurs primarily through the metal absorber plate of the solar collector. When solar radiation strikes the blackened surface, it increases the thermal energy of the plate. This thermal energy is then conducted to the air flowing across or beneath the collector surface. The effectiveness of conduction depends on the thermal conductivity of the material and the temperature gradient established between the surface and the air. Materials like aluminum or galvanized iron are preferred due to their excellent thermal properties.

- Convection: Once the air is heated via conduction in the collector, natural or forced convection transports the warm air into the drying chamber. In passive systems, natural convection arises from the buoyancy of the warm air, causing it to rise and flow through the system. In active systems, fans may be used to increase airflow. As the hot air enters the chamber, it contacts the moist surfaces of the produce, absorbing moisture in the process. This heat transfer from hot air to produce is a classic example of convective drying, and the rate of drying depends significantly on airflow velocity, temperature, and relative humidity.
- Radiation: Although the drying chamber is not directly exposed to sunlight, radiation still plays a minor role in heating the internal surfaces of the chamber and the produce indirectly. The walls of the chamber may absorb some heat and re-radiate it as infrared radiation, contributing to warming the produce. However, this is less significant compared to conduction and convection in the indirect dryer.
- Insulation: To reduce heat loss and improve thermal efficiency, the collector and chamber are insulated using materials like glass wool, polystyrene, or foam boards. These materials minimize heat transfer to the surrounding environment, ensuring more of the collected thermal energy is directed toward drying. Proper insulation also helps maintain a stable internal temperature, which is crucial for consistent drying performance.
- Air Inlets and Outlets: The performance of an indirect solar dryer greatly depends on its air circulation system. The air inlet is typically located at the base or side of the collector to allow ambient air to enter and be heated. The outlet vents are located at the top or rear of the drying chamber to

enable moisture-laden air to escape. Proper design of these vents ensures a continuous flow of air, preventing humidity build-up and allowing for efficient moisture removal. In active systems, blowers or exhaust fans may be employed to enhance airflow and control drying rates.

2.1.1 Components of the Indirect Solar Dryer

An indirect solar dryer consists of several major parts:

- Solar collector: Captures and converts solar energy into heat.
- Drying chamber: Where the produce is arranged in trays, protected from direct solar radiation.
- Transparent glazing: Typically glass or clear plastic on the collector to trap solar radiation.
- Air ducts or passages: Direct the heated air into the drying chamber.
- Insulation: Maintains the internal temperature and reduces losses.
- Ventilation vents: Control airflow and moisture escape.

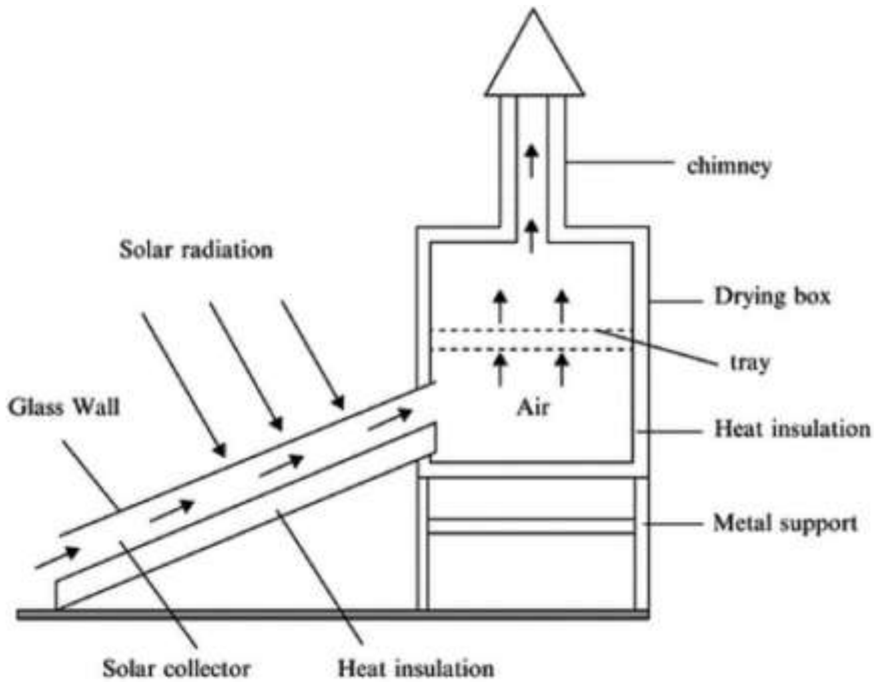

Figure 2.1.1: Labelled diagram of indirect solar dryer

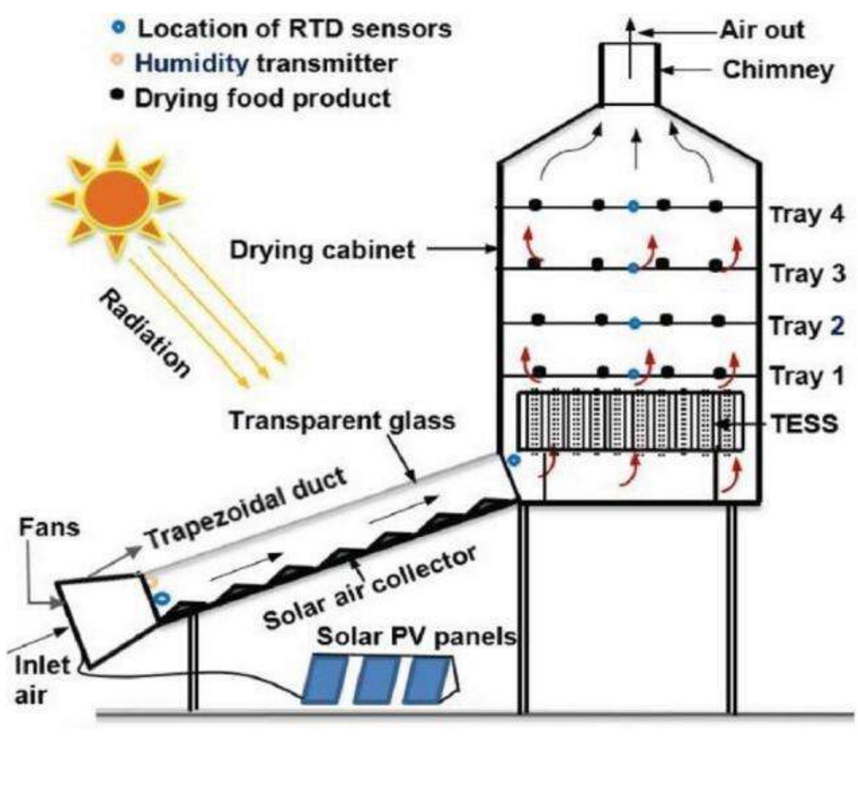

Figure 2.1.2: Labelled diagram of indirect solar dryershowing components and airflow.

2.2 Working Principle of Greenhouse Solar Dryer

The greenhouse solar dryer operates on the fundamental principles of solar energy conversion and heat transfer mechanisms namely radiation, conduction, and convection. This system utilizes a transparent or translucent covering material, usually polycarbonate, polyethylene, or glass, to allow the penetration of solar radiation into an enclosed drying chamber. Once inside, the radiation is absorbed by the interior surfaces and converted into thermal energy, which raises the ambient temperature within the chamber, facilitating moisture evaporation from the products placed inside. The greenhouse design ensures improved protection from environmental factors such as wind, rain, dust, and pests, while maintaining a relatively high and stable drying temperature. This system is suitable for a wide range of agricultural products, including fruits, vegetables, fish, meat, and spices.

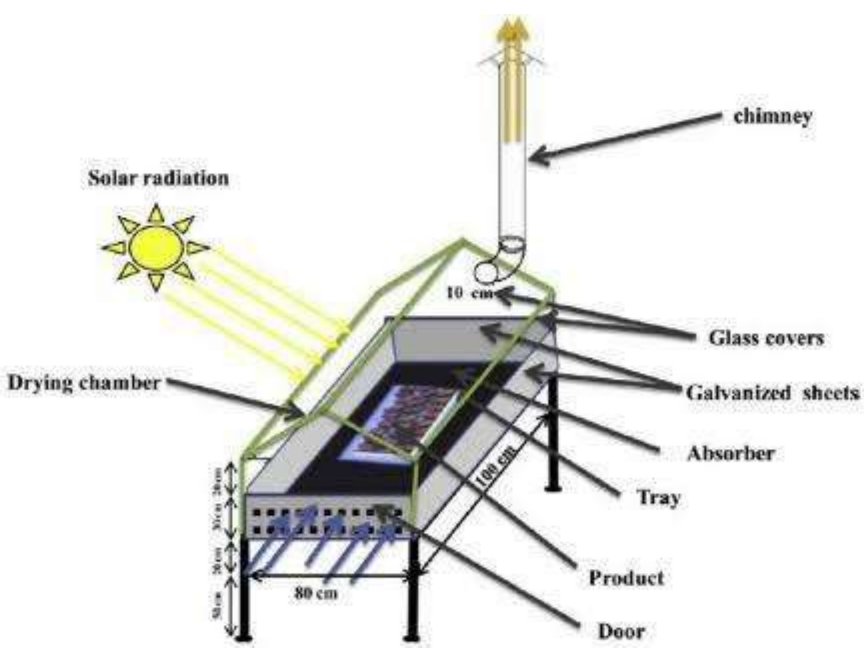

Figure 2.2.1: Schematic diagram of a typical greenhouse solar dryer

- Solar Radiation and Absorption: The primary energy input in a greenhouse dryer is solar radiation. Shortwave radiation from the sun passes through the transparent glazing material and is absorbed by dark-colored surfaces within the chamber typically the floor, tray supports, or specialized black absorber plates. These surfaces convert the radiant energy into heat, which then warms the air inside the dryer. According to Abubakar et al. (2021), up to 80% of the incoming radiation can be effectively trapped and utilized within a well-designed greenhouse dryer. The absorbed radiation raises the chamber temperature significantly above ambient, thus creating a conducive environment for efficient moisture evaporation.
- Conduction: This plays a role in transferring the absorbed heat from the dryer's surfaces to the product trays and ultimately to the agricultural products. The absorber surface (e.g., black-painted metal or concrete floor) conducts heat to the drying trays through their physical contact or supporting frame. This heat transfer increases the temperature of the produce, which in turn enhances the rate at which internal moisture diffuses to the surface and evaporates. Thermal conductivity of the materials used in the floor and trays significantly influences the drying rate. Metallic frames and trays are often employed due to their superior conductive properties.
- Convection: Natural or forced convection facilitates the transfer of heat from the warm internal air to the surface of the drying product, and also aids in removing moisture-laden air from the system. As the interior air gets heated, it becomes less dense and rises, creating a natural convection current. Fresh ambient air enters through strategically positioned air inlets, replaces the

moist air, and exits through outlets or ventilators located at the top or opposite end of the dryer. This airflow system ensures continuous removal of moisture vapor and maintains drying efficiency. In some designs, small DC fans powered by photovoltaic panels are used to enhance airflow (forced convection), particularly in larger greenhouse dryers (Azad et al., 2020).

- Radiation Trapping (Greenhouse Effect): One of the most defining principles of the greenhouse dryer is the radiation trapping mechanism. Incoming shortwave solar radiation passes through the transparent roof, but as the internal surfaces re-emit this energy as longwave infrared radiation, the glazing material becomes partially opaque to it, thereby trapping the heat inside. This phenomenon is known as the greenhouse effect and is critical to maintaining higher internal temperatures over long durations. As reported by Kumar and Tiwari (2019), internal temperatures in greenhouse dryers can exceed ambient temperatures by 15–30°C depending on weather conditions and design efficiency.
- Insulation: Thermal insulation is essential to minimizing heat loss and maintaining uniform temperature distribution. The base and side walls of the dryer are often insulated with materials such as polystyrene, foam boards, or insulating bricks to reduce conductive heat loss to the surrounding. Good insulation improves the thermal retention capacity of the system and contributes to energy efficiency. Additionally, air-tight sealing of joints and structural components helps prevent unintended convective losses (Sahu et al., 2020).

2.2.1 Components and Functions

A standard greenhouse solar dryer comprises several functional components:

- Transparent Roof or Covering: Usually made from UV-stabilized polyethylene or polycarbonate, this allows high solar transmissivity and aids in trapping heat via the greenhouse effect.
- Drying Trays: These are arranged in tiers for optimal space usage. Trays are often made from perforated metal or food-grade mesh to allow upward airflow.
- Absorber Base or Floor: Painted black to maximize solar absorption and made of high thermal mass materials to retain heat.
- Air Inlets: Located near the base of the dryer to draw in cooler, dry air from the environment.
- Air Outlets or Vents: Typically found at the top or rear, facilitating the expulsion of moist air and promoting air circulation.
- Supporting Frame: Constructed from wood, aluminum, or steel to support the structure and trays.
- Optional Fans and PV System: In hybrid systems, small solar-powered fans are added to enhance air movement, especially during cloudy weather.

The efficiency of a greenhouse solar dryer hinges on the synergy between these components. The drying process begins with solar radiation entering the system, which is absorbed and converted to heat. This heat is conducted to the drying products and convected around the chamber, while the greenhouse effect ensures thermal retention. Simultaneously, moisture evaporated from the products is carried away by airflow, completing the drying cycle. This integrated mechanism allows the greenhouse solar dryer to function effectively even in marginal weather conditions, offering superior product quality, reduced drying times, and protection from contaminants.

2.3 Classification of Solar Dryers

Solar dryers can be broadly classified based on design configuration, mode of air circulation, and energy source. However, the most common classification scheme distinguishes solar dryers into passive and active systems. These categories further branch into subtypes such as direct, indirect, and mixed-mode dryers. Each system possesses unique structural and functional characteristics that influence drying efficiency, heat transfer dynamics, airflow control, and suitability for specific crops and regions.

2.3.1 Passive Solar Dryers

Passive solar dryers operate without external mechanical energy input for airflow, relying solely on natural convection driven by solar heating and buoyancy forces. These systems are often simpler, cheaper, and easier to construct and maintain, making them highly suitable for small-scale rural farmers.

- Direct Passive Solar Dryers: In direct passive dryers, the product is placed in an enclosed chamber with a transparent cover (often glass or UV-treated polycarbonate) that allows solar radiation to strike the product surface directly. The drying chamber traps heat through the greenhouse effect, raising internal temperature and accelerating moisture evaporation (Esper & Mühlbauer, 1998). While this method enhances drying speed compared to open sun drying, the direct exposure of crops to sunlight can degrade color, nutrients, and aroma in sensitive produce such as tomatoes or herbs.Typical components include:Transparent cover for solar gain, vented walls for moisture-laden air escape, Drying trays or racks for product placement, Air inlet and outlet ports for passive airflow. These systems are best suited for products that tolerate or benefit from direct sun exposure.

- Indirect Passive Solar Dryers: In contrast, indirect passive dryers use a separate solar collector to heat air, which is then directed into a drying chamber housing the product. The drying air absorbs moisture from the product without exposing it to direct sunlight, thus preserving color, flavor, and nutritional value (Sodha et al., 1985). The collector typically consists of a black-painted absorber surface beneath a transparent cover, enclosed in an insulated box to enhance thermal efficiency.Key features include:Solar air heater (collector), Insulated drying chamber with trays, Natural convection vents for airflow, No external fan or electricity. These systems are particularly useful for drying heat-sensitive crops such as vegetables, spices, or medicinal plants, offering improved hygiene and reduced contamination risks.
- Mixed-Mode Passive Dryers: This combine direct and indirect drying principles. In this setup, the drying chamber receives heat both from direct solar radiation and from preheated air from a solar collector. This configuration enhances drying efficiency and reduces drying time while minimizing the downsides of prolonged direct exposure (Bala, 2020).

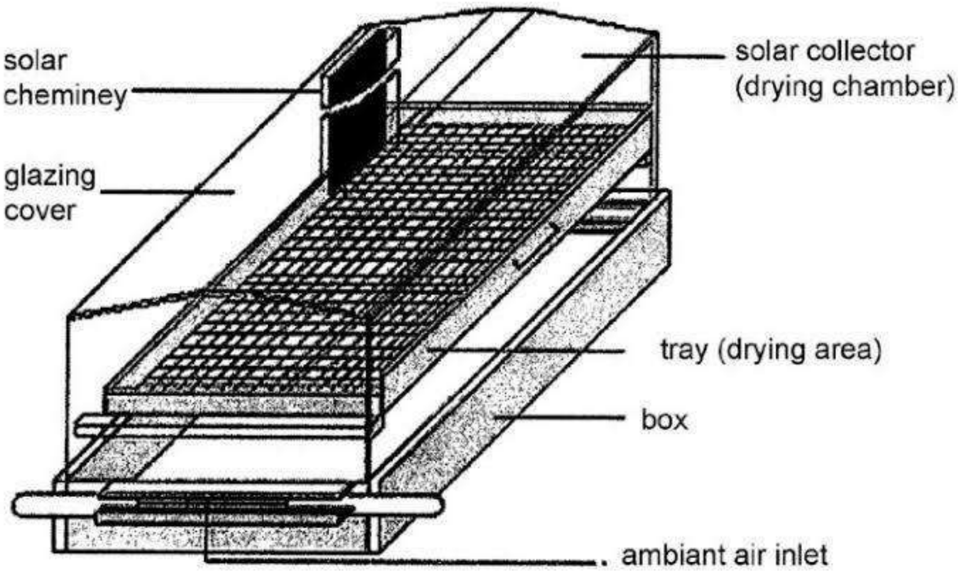

Figure 2.3.1: Layout of a Direct Passive Solar Dryer

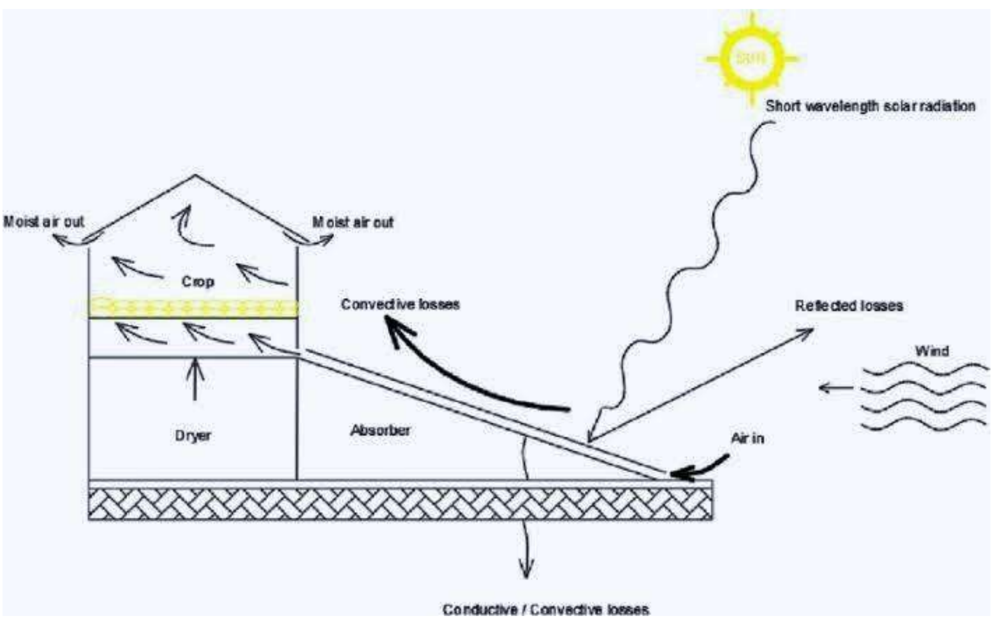

Figure 2.3.2: Layout of an Indirect Passive Solar Dryer

2.3.2 Active Solar Dryers

Active solar dryers incorporate mechanical systems such as fans or blowers powered by electricity or photovoltaic panels to regulate airflow and enhance heat distribution within the system. These dryers are more effective for large-scale or commercial drying operations due to their ability to maintain constant airflow, uniform temperature, and faster drying cycles regardless of ambient conditions.

- Direct Active Solar Dryers: In direct active systems, fans circulate hot air across the product while it is exposed to direct sunlight. Though similar to direct passive dryers in design, the mechanical airflow improves drying rate and uniformity. However, careful regulation is required to avoid nutrient degradation or over-drying (Sharma et al., 2009).
- Indirect Active Solar Dryers: These dryers use mechanical fans to force air through the solar collector and drying chamber. The forced airflow promotes turbulent mixing, enhancing heat and mass transfer. Because products are not exposed to direct radiation, indirect active dryers are well suited for high-value, perishable crops like fruits, vegetables, and medicinal plants.Components typically include:Solar collector (flat plate or concentrator), Drying chamber (insulated, multi-tiered), Electric or solar-powered fans, Thermostatic control (optional)
- Hybrid or Mixed-Mode Active Dryers: This combine solar and auxiliary energy sources (e.g., biomass burners or electrical heaters) to ensure continuous drying under cloudy conditions or at night. This versatility makes them suitable for industrial or year-round applications (Fudholi et al., 2014).

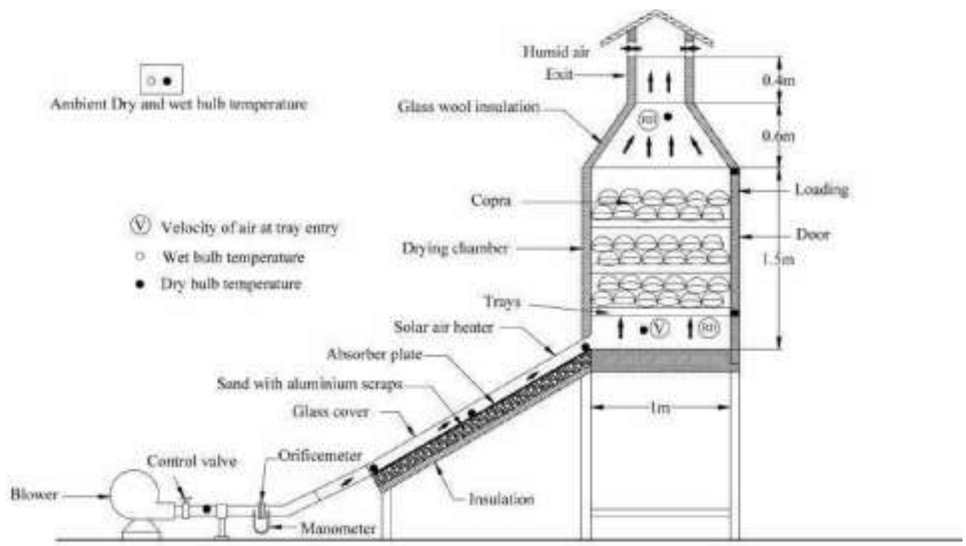

Figure 2.3.3: Layout of an Indirect Active Solar Dryer system

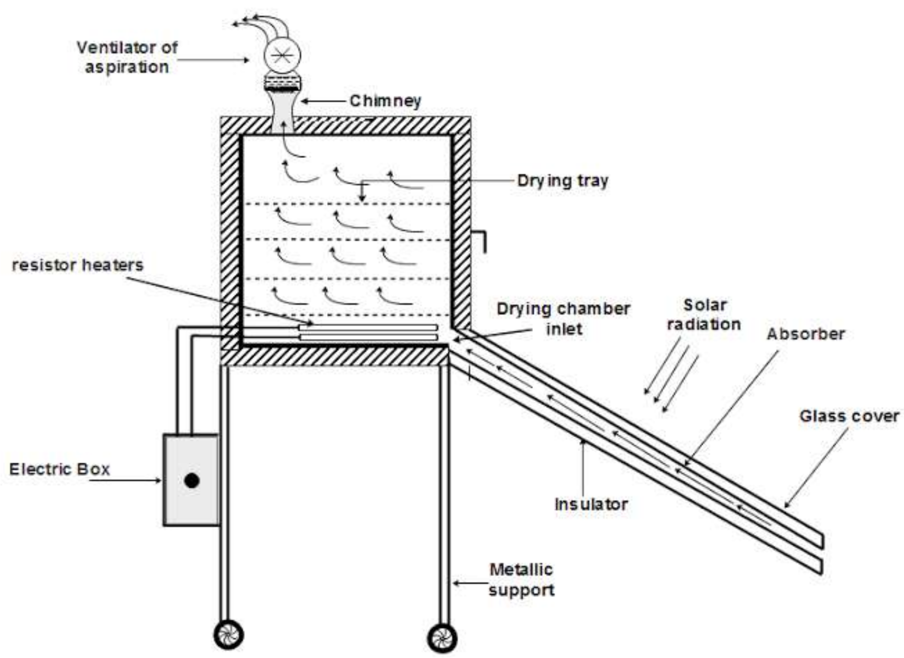

Figure 2.3.4: Layout of Hybrid Solar Dryer

Each classification serves different needs based on crop type, environmental conditions, user preferences, and resource availability. For instance, while passive dryers offer low-cost, eco-friendly solutions for rural farmers, active dryers provide higher throughput and precision drying required in commercial operations. The choice of dryer influences not only the thermal performance and drying rate, but also the nutritional and organoleptic quality of the dried product, which is central to the current research on the comparative performance of direct sun drying, indirect, and greenhouse solar dryers.

2.4 Solar Drying and Its Relevance

Solar drying represents a sustainable and energy-efficient method for preserving agricultural produce, utilizing the sun's radiant energy to reduce moisture content in crops. This process significantly minimizes microbial growth and enzymatic activity, which are primary causes of postharvest spoilage. In many tropical and subtropical regions, traditional open sun drying has been a common preservation method. However, it is often constrained by uncontrollable environmental factors such as rain, wind, pests, dust, and uneven drying, which can degrade product quality (Esper & Mühlbauer, 1998; Bala, 2020).Modern solar drying technologies such as direct, indirect, and greenhouse solar dryers have emerged to address these limitations, offering controlled drying environments that improve drying efficiency, reduce contamination, and ensure uniform product quality. These systems also help farmers reduce postharvest losses and increase income by preserving surplus produce for future sales or processing (El-Sebaii & Shalaby, 2012). In regions lacking access to electricity or other fuel sources, solar dryers serve as cost-effective, low-maintenance alternatives that contribute to food security and environmental conservation.The relevance of solar drying extends beyond its technical benefits to its alignment with global sustainability goals. By replacing fossil-fuel-dependent drying systems, solar dryers reduce greenhouse gas emissions and reliance on non-renewable energy sources. Furthermore, solar dryers can be designed to accommodate a wide variety of crops including tomatoes, peppers, fish, cassava, and herbs making them adaptable for small- and medium-scale farmers in diverse climatic zones (Forson et al., 2007; Fudholi et al., 2014).The growing emphasis on cleaner technologies and rural development has heightened the importance of solar drying in agricultural value chains. This makes it a vital component in postharvest technology, especially in sub-Saharan Africa and other regions where energy access is limited and food preservation remains a challenge.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Construction Materials for the Solar Dryers

- High-density fiber (HDF) plywood boards: were used to form the outer casing of the indirect solar dryer, covering the sides and base of both the drying chamber and the solar collector. This material was chosen due to its smooth finish, ease of cutting, and moderate thermal resistance, which helped reduce heat loss from the system. HDF is also cost-effective and locally available, making it suitable for low-resource settings. When properly sealed or painted, it offers decent durability and structural support for enclosing the dryer while maintaining a clean, professional appearance.
- Transparent glass: was used as the glazing material for the solar collector in the indirect dryer and for enclosing the entire structure of the greenhouse dryer. Its primary role was to allow solar radiation to penetrate into the system while trapping long wave heat through the greenhouse effect. Glass was chosen over plastic alternatives due to its superior clarity, durability, and resistance to UV degradation. In the indirect dryer, a combination of 10mm inner and 5mm outer glass was used to enhance insulation, reduce heat losses, and maintain structural integrity under outdoor exposure.
- Black-painted metallic iron sheets: were used as the absorber within the solar collector of the indirect dryer. Their function was to absorb incoming solar radiation and convert it into heat, which in turn raised the temperature

of the air within the collector. The black coating increased the surface's ability to absorb solar energy by minimizing reflectivity, while the metal's high thermal conductivity allowed for efficient heat transfer to the passing air. This combination enhanced the overall thermal performance of the dryer.

- Fiber material: was used as insulation within the walls of the indirect solar dryer to minimize heat loss. It was placed between the inner and outer layers of the dryer's structure to prevent thermal conduction from the heated interior to the cooler external environment. Fiber was selected because of its low thermal conductivity, lightweight nature, and ease of installation. This helped maintain higher internal temperatures, improved drying efficiency, and reduced fluctuations caused by external weather conditions.

- Drying Trays: Instead of wire mesh, plastic trays were used to hold the pepper samples. These trays were wrapped with aluminum foil to enhance hygiene and reflectivity, minimizing contamination and improving drying surface conditions.

- Angle iron: was used to construct the metallic stand for the indirect solar dryer. It provided strong structural support for both the collector and the drying chamber, ensuring the entire unit was elevated and stable. The use of metal offered durability and resistance to bending or warping under load or prolonged sun exposure.

- Aluminum angle: was used to seal exposed gaps along the edges of the solar collector in the indirect dryer, particularly where the glass met the wooden or metallic frame. Its purpose was to prevent rainwater from seeping into the collector during wet conditions and to reduce heat loss through structural joints. Aluminum was chosen for this sealing role due to its corrosion resistance, ease of bending, and durability in outdoor environments. This helped maintain the integrity of the collector and ensured consistent thermal performance.

- 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.

- 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.

- 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 Instruments Used

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

- Digital Multimeter with Sensor Probe Model DM8100: 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 3.2.4 Digital Weighing Scale

3.3 Construction Process

The construction process commenced with meticulous planning and detailed design schematics to guide the fabrication of both the indirect and greenhouse solar dryers. Accurate dimensional measurements were taken to ensure that each component would align properly during assembly.

For the indirect solar dryer, the solar collector was constructed using a flat metallic plate measuring 123 cm in length, 57 cm in breadth, and 21 cm in height. This plate functioned as the primary absorber of solar radiation, intended to heat the incoming air before it passed into the drying chamber. The drying chamber (cabinet), designed to house the produce trays, was built with a length of 85 cm and a breadth of 52.5 cm.At the upper rear section, a chimney was installed and slightly tilted to permit rainwater drainage. The chimney components were fabricated with the following dimensions:

- Chimney back: 38 cm × 28.5 cm
- Chimney sides: 20.5 cm × 38 cm
- Chimney head: 28.5 cm (length) × 33 cm (breadth) × 12.5 cm (height)

An access door measuring 72 cm in length and 67 cm in breadth was incorporated into the drying cabinet to allow easy handling of trays and inspection of the drying process.

Figure 3.3.1 during welding process of the indirect solar dryer

The frame components, including the collector plate and structural elements, were transported to a local welding workshop located in GRA, Ilorin, behind the

Governor’s Office. Welding was carried out under close supervision to ensure strict adherence to the specified dimensions and design.

Figure 3.3.2 welded framework of the indirect solar dryer

Upon completion, the assembled frame was returned to the department and painted using automobile-grade black paint to enhance solar absorption. After the paint dried, the entire unit was mounted on a decking platform behind Physics Laboratory A, selected for its elevation and lack of shading obstructions. A ladder was used to transport and position the dryer on the platform.The structural casing was constructed using High-Density Fibreboard (HDF) plywood, which was used to enclose the dryer’s sides. The top portion of the collector was covered with transparent glass to allow sunlight penetration. Two glass layers were installed:

- Inner layer: 10 mm thick
- Outer layer: 5 mm thick

The edges were sealed using aluminum angles, while rubber lining was added to prevent water ingress during rainfall. Additionally, hinges, handles, and locks were installed to facilitate ease of access and improve operability. The assembly process involved the use of nails, screws, and hammers to ensure structural integrity. Following completion, the entire unit was thoroughly cleaned, both internally and externally.

Figure 3.3.3 completed construction of the indirect solar dryer

Work was also undertaken on an existing greenhouse solar dryer, which required repairs to restore its operational integrity. The main structural dimensions of the greenhouse dryer were:

- Overall body: 154.5 cm (length) × 104.5 cm (breadth) × 100 cm (height)
- Raised head section: 104.5 cm (length) × 55 cm (breadth) × 49.5 cm (height)

A new collector plate was fabricated and installed, measuring 149 cm in length and 102 cm in breadth. Repair work included replacing broken glass panels and rebuilding the door. After repairs, the entire unit was cleaned, reassembled, and prepared for experimental use.

Figure 3.3.4 completed construction of the greenhouse solar dryer

Both the indirect and greenhouse solar dryers were mounted side by side on the same elevated platform and aligned in the same direction to ensure uniform solar exposure during testing. This strategic placement helped to maintain consistent environmental conditions and optimize performance comparison between the two systems throughout the experimental period.

3.4 Experimental Setup

The experimental setup began with the preparation of our sample fresh tomatoes (Solanum lycopersicum) used for the drying process. The tomatoes were purchased from Mandate Market in Ilorin and then brought to the laboratory for preparation. The tomatoes were washed with clean water to remove any surface contaminants. After washing, the stems were removed, and each tomato pod was carefully 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 tomato after loading. The sliced tomato 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 tomato slices. The actual weight of the tomato was obtained by subtracting the tray-and-foil weight from the total weight. These trays were then placed inside their respective drying systems, 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: Tomatoes 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 9:00 am to 5:00 pm daily, across a three-day 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 tomato 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 tomato slices 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, moisture removal capacity, and drying performance under real environmental conditions.

3.5 Performance Evaluation Parameters

To assess the effectiveness of the solar dryers used in this research, which are greenhouse solar dryer, indirect solar dryer, and open sun drying. Several thermal and physical parameters were calculated. These parameters help in understanding the drying behavior, energy utilization, and efficiency of the systems. The main parameters considered include moisture content, drying rate, and thermal efficiency.

- Moisture content: This is a critical parameter in drying studies, as it reflects the amount of water present in the product at any given time. It determines the quality and shelf-life of dried products. During drying, the moisture content decreases progressively until it reaches a level safe for storage. Inadequate drying can lead to microbial growth, spoilage, and loss of quality, while over-drying may reduce nutrient content and increase energy usage. In this research, the moisture content was calculated on a wet basis, which is more common in food processing studies. The formula used is:

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

$$M_i = Initial\ Weight$$

M_f = Final Weight

This formula provides the moisture removed relative to the original weight of the material. For each drying method, weights were recorded hourly, and the reduction in mass was used to compute the moisture loss throughout the drying period. Accurate determination of moisture content is essential for comparing the drying performance of different systems. This approach is widely used in solar drying studies, particularly in agricultural products like cassava, tomatoes, and peppers (Mohammed et al., 2021; Bala, 1997; Onuoha & Obetta, 2010).

- Drying rate: This is another essential parameter that indicates the speed at which moisture is removed from a substance. It helps in understanding the drying kinetics and how efficiently the solar dryer performs over time. A higher drying rate suggests faster moisture removal, better thermal performance, and reduced drying time, all of which contribute to energy savings and product quality. It is measured in grams per hour (g/h) or kg/h and expressed as:

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

$$M_i = Initial\ Weight$$

$$M_f = Final\ Weight$$

$$T = Time\ interval\ in\ Seconds$$

For Wet Basis:

$Drying\ Rate = \frac{M_i - M_f}{T} \times 100$

The drying rate gives insights into the drying behavior at each stage. For example, drying is usually faster in the initial stage when the moisture content is high and slows down as the product loses moisture. These trends were carefully observed and calculated during the Eight-day experimental period in this study. A steady or high drying rate usually reflects good heat and mass transfer characteristics of the dryer (Hossain & Bala, 2007; Janjai & Bala, 2012). By comparing drying rates across the greenhouse, indirect, and open sun drying methods, one can determine which system achieves quicker drying with minimal nutrient and quality loss.

- Thermal efficiency (or drying efficiency): This is a measure of how well the solar dryer converts incident solar energy into useful energy for moisture removal. It reflects the effectiveness of the system in utilizing available solar radiation to generate heat that facilitates drying. The thermal efficiency was calculated using the formula:

$$\eta_{cdg} = \frac{\dot{M} \quad C_{pa}(T_i - T_O)}{A_c I_g} \qquad Where:$$

$$C_{pa}: Specific\ Heat\ Capacity\ of\ Air$$

$$M : Mass\ of\ Sample$$

$$T_i : Collector\ Temperature$$

$$T_O : Ambient\ Temperature$$

$$I_g : Global\ Solar\ Radiation$$

$$A_c : Area\ of\ the\ collector$$

This equation helps determine how much of the captured solar energy was used in evaporating moisture from the product. A higher efficiency indicates a better-performing solar dryer with minimal energy losses. The efficiency is affected by several factors, including the design of the collector, insulation, airflow, ambient temperature, and solar intensity. For this study, efficiency values were calculated for both the indirect and greenhouse dryers using the recorded solar radiation and moisture loss data. Solar radiation was measured hourly using a pyranometer or solar meter, and temperature data helped in validating thermal performance.

This method is frequently adopted in solar drying literature (Bukola & Ayoola, 2008; Janjai & Bala, 2012) and serves as a benchmark to compare the performance of different solar drying systems.

3.6 Sample Calculations using the experimental Data (Day1- Day 6)

Calculation of Moisture content of Tomato

Tray 6- Greenhouse (Day 1)

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

Initial weight M_i = 612g

Final weight M_f = 287g

- Time: 11:30am

$$Moisture\ Content = \frac{612 - 287}{287} = 1.132g$$

- Time : 12:30pm

$$Moisture\ Content = \frac{580 - 287}{287} = 1.020g$$

Tray 5- Open Sun Drying (Day 1)

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

Initial weight M_i = 598g

Final weight M_f= 311g

- Time: 11:30am

$$Moisture\ Content = \frac{598 - 311}{311} = 0.922g$$

- Time: 12:30pm

$$Moisture\ Content = \frac{570 - 311}{311} = 0.832g$$

Tray 1- Indirect (Day 1)

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

Initial weight M_i = 655g

Final weight M_f= 310g

- Time: 11:30am

$$Moisture\ Content = \frac{655 - 310}{310} = 1.112g$$

- Time : 12:30pm

$$Moisture\ Content = \frac{645 - 310}{310} = 1.080g$$

Calculation of Drying Rate

Tray 1 – Indirect (Day1)

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

Initial Weight = 655g

Final Weight = 310g

- Time : 11:30am

$$Drying\ Rate = \frac{655 - 310}{60 \times 60} = 0.095g \quad = \frac{655 - 310}{3600} \times 100 = 9.5\%$$

- Time : 12:30pm

$$Drying\ Rate = \frac{645 - 310}{60 \times 60} = 0.093g \quad = \frac{645 - 310}{3600} \times 100 = 9.3\%$$

Tray 6 – Greenhouse (Day1)

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

Initial Weight = 612g

Final Weight = 287g

- Time : 11:30am

$$Drying\ Rate = \frac{612 - 287}{60 \times 60} = 0.902g \quad = \frac{612 - 287}{3600} \times 100 = 90.2\%$$

- Time : 12:30pm

$$Drying\ Rate = \frac{580 - 287}{60 \times 60} = 0.813g \qquad = \frac{580 - 287}{3600} \times 100 = 81.3\%$$

Tray 5 – Open Sun Drying (Day 1)

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

Initial Weight = 598g

Final Weight = 311g

- Time : 11:30am

$$Drying\ Rate = \frac{598 - 311}{60} = 4.78g \qquad Drying\ Rate = \frac{598 - 311}{60\ \times 60} = 0.079g$$

- Time : 12:30pm

$$Drying\ Rate = \frac{570 - 311}{60} = 4.31g \qquad Drying\ Rate = \frac{570 - 311}{60\ \times 60} = 0.071g$$

Efficiency Calculation

Tray 1 – Indirect (Day 1)

$$\eta_{cdg} = \frac{m\ C_{pa}(T_i - T_o)}{A_c I_g}$$

Where;

C_{pa} : Specific capacity of air (1.005J/g/ ^{o}C)

I_g : Global solar radiation

T_i : Temperature of the collector

T_o : Ambient temperature

m : Mass of the sample

A_c : Area of the collector (area of the cube)

Where;

w = 57cm = 0.57m

h = 21cm = 0.21m

l = 123cm = 1.23m

$$A = 2(lw + wh + lh)$$

$$A = 2(1.23 \times 0.57 + 0.57 \times 0.21 + 1.23 \times 0.21)$$

$$A = 2(0.7011 + 0.1197 + 0.2583)$$

$$A = 2(1.0791)$$

$$A = 2.1582 \approx 2.16m^2$$

- Time : 09:40am

$$\eta_{cdg} = \frac{m\, C_{pa}(T_i - T_o)}{A_c I_g} = \frac{655 \times 1.005(36.2 - 27.4)}{2.16 \times 453} = 5.9202$$

- Time : 10:40pm

$$\eta_{cdg} = \frac{m\, C_{pa}(T_i - T_o)}{A_c I_g} = \frac{645 \times 1.005(48.7 - 34.5)}{2.16 \times 641} = 6.648$$

Tray 6 – Greenhouse (Day 1)

$$\eta_{cdg} = \frac{m\, C_{pa}(T_i - T_o)}{A_c I_g}$$

Where;

C_{pa} : Specific capacity of air (1.005J/g/ ^{o}C)

I_g : Global solar radiation

T_i : Temperature of the collector

T_o : Ambient temperature

m : Mass of the sample

A_c : Area of the collector (area of the cube)

Where;

$$A = l \times b$$

l = 1.49m

b = 1.02m

$$A = 1.49 \times 1.02$$

$$A = 1.52m^2$$

- Time : 11:30am

$$\eta_{cdg} = \frac{m\ C_{pa}(T_i - T_o)}{A_c I_g} = \frac{612 \times\ 1.005(28.4 - 27.4\ )}{1.52 \times 453} = \frac{615.06}{688.5} = 0.893$$

- Time : 12:30pm

$$\eta_{cdg} = \frac{m\ C_{pa}(T_i - T_o)}{A_c I_g} = \frac{580 \times\ 1.005(41.2 - 34.5)}{1.52 \times 641} = \frac{3905.43}{974.32} = 4.008$$

CHAPTER FOUR

4.0 RESULT AND DISCUSSION

This study rigorously evaluated the effectiveness of various solar drying systems for dehydrating tomatoes, with the primary objective of identifying the most efficient method while simultaneously highlighting the distinct advantages associated with each drying technique employed. Over a span of six days, an initial sample of 655g of tomatoes was reduced to 324g using an indirect solar dryer. In comparison, a greenhouse solar dryer effectively decreased a 612g sample of tomato to 287g, while open-air drying resulted in a reduction of 598g of tomato to 311g. The parameters measured during these experiments included (a) solar radiation incident on the collector, (b) ambient temperature, (c) temperatures within the drying chambers of both the indirect and greenhouse solar dryers, (d) collector temperature in the indirect solar dryer, (e) ambient humidity levels, (f) moisture content of the dried product, and the overall drying rate, adhering to the international standards established by ASABE/ASAE (2007) for solar air collectors. Temperature measurements were conducted at various points within the collectors and chambers utilizing a K-type thermocouple multimeter, with the drying regimen commencing daily at 8:00 AM and concluding at 4:00 PM, 4:30PM, 5:00PM, and 5:30PM respectively.

CHAPTER FIVE

5.0 CONCLUSION

This study was carried out to design, construct, and evaluate the comparative performance of three different drying methods which are open sun drying, an indirect solar dryer, and a greenhouse solar dryer for preserving tomato. The primary goal was to assess which of the systems provides the most efficient and effective drying conditions in terms of moisture removal, temperature stability, and overall performance.

The experimental procedure involved drying tomato slices under each of the three systems, with hourly measurements taken for temperature, humidity, solar radiation, and sample weight across several days. The performance of each system was evaluated based on moisture content reduction, drying rate, and thermal efficiency.

From the data obtained, it was observed that the greenhouse solar dryer consistently recorded the highest internal temperature, followed closely by the indirect solar dryer, while direct sun drying (open sun) showed the lowest and most fluctuating temperature values. These temperature patterns had a direct impact on drying performance. The greenhouse dryer achieved the fastest moisture reduction, indicating a more stable and controlled drying environment. The indirect dryer also showed improved performance compared to open sun drying, particularly in maintaining hygiene and reducing contamination risks. In terms of drying efficiency, both the greenhouse and indirect systems outperformed the open sun method, demonstrating the advantage of using structured drying systems in minimizing spoilage, improving drying speed, and preserving nutritional quality.

The findings from this project confirm that incorporating engineered solar dryers particularly the greenhouse and indirect type can significantly improve the drying of tomato, contributing to better post-harvest handling, reduced losses, and improved product quality. The results encourage the adoption of such systems among local farmers and food processors, especially in rural areas where electricity is not readily available.

5.1 RECOMMENDATIONS

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

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IN PARTIAL FULFILMENT FOR THE AWARD OF HIGHER NATIONAL DIPLOMA (HND) IN SCIENCE LABORTORY TECHNOLOGY

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2024/2025 SESSION

CERTIFICATION

This is to certify that this project work has been written by **GROUP THREE** with matric numbers **HND/23/SLT/FT/0828, HND/23/SLT/FT/0064, HND/23/SLT/FT/0013, HND/23/SLT/FT/0546, HND/23/SLT/FT/0366, HND/23/SLT/FT/0190,** 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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EXTERNAL EXAMINER **DATE**

DEDICATION

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

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May God bless and keep you all (amen).

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

In recent years, the intersection of agricultural sustainability and renewable energy application has become a critical area of investigation, particularly in regions where post-harvest losses continue to undermine food security and economic resilience. Among the major horticultural crops grown across the region, tomatoes (Solanum lycopersicum) hold significant nutritional and economic importance. However, their high water content and delicate skin structure render them highly susceptible to rapid post-harvest spoilage under ambient tropical conditions. According to Olumekun and Akinoso (2017), post-harvest losses in tomatoes in Nigeria are estimated at over 40%, largely due to inadequate preservation and transportation infrastructure. These losses represent not only a threat to food supply but also a financial setback for smallholder farmers and local vendors who depend on seasonal harvests for income generation.

Traditional preservation methods such as open sun drying are still widely used, especially in rural and semi-urban communities. While sun drying offers zero operational costs and minimal technical barriers, it poses several disadvantages including contamination by dust and insects, uneven drying, dependence on clear weather, and vulnerability to spoilage from sudden rainfalls or nocturnal moisture absorption (Bala & Mondol, 2019). These challenges have sparked a growing interest in solar drying systems, which offer enhanced environmental control while harnessing renewable energy to dry crops more efficiently.

Solar dryers are engineered systems designed to absorb solar radiation and convert it into thermal energy for the purpose of controlled dehydration. Unlike traditional sun drying, solar dryers can protect crops from contamination and accelerate moisture removal, resulting in better preservation of color, nutrients, texture, and overall product quality (Motevali et al., 2021). The application of solar energy in food preservation aligns with global efforts to promote renewable energy use in agriculture and reduce post-harvest losses, particularly in regions with high solar radiation potential.

Three main types of solar dryers have emerged in both research and practical deployment: direct solar dryers, indirect solar dryers, and greenhouse solar dryers. Each of these configurations has unique advantages and design limitations. In a direct solar dryer, the product is placed inside an enclosed chamber covered with transparent material that allows solar radiation to enter and heat the product directly. While this setup facilitates rapid heating and drying, it may result in photodegradation of heat-sensitive nutrients due to direct exposure to ultraviolet rays (Ekechukwu & Norton, 2019). Indirect solar dryers overcome this limitation by using a separate solar collector to heat air, which is then channeled into a drying chamber where the crop is placed. This indirect heating process ensures better product quality by minimizing exposure to harmful rays and reducing surface hardening (Hossain & Bala, 2007). Greenhouse dryers combine features of both systems by enclosing the entire drying space in a greenhouse structure, which can maintain higher internal temperatures through the greenhouse effect while offering protection from external environmental factors (Ongen et al., 2020).

Open sun drying, considered the most rudimentary form of direct drying, has been used for centuries across tropical and subtropical regions. In this method, tomatoes are spread out under the open sky and exposed to direct sunlight. While the process requires no technological input, it is fraught with inefficiencies. Research by Adesina and Onwuka (2020) revealed that open sun drying is highly weather-dependent, unhygienic, and yields inconsistent moisture removal, often resulting in microbial contamination and nutrient degradation. These challenges have led to the development of more controlled alternatives like indirect and greenhouse solar drying systems, which provide better thermal regulation and protection against environmental hazards.

In indirect solar dryers, thermal energy is first absorbed by a collector unit, which heats up ambient air. This hot air is then circulated either naturally or by forced convection into a separate drying chamber containing the crop. This design isolates the drying material from direct solar radiation, reducing the risk of UV degradation and excessive surface drying. A study by Abano and Amoah (2019) comparing tomato drying in indirect and open sun methods showed that indirect dryers preserved better color, taste, and vitamin C content, and reduced the microbial load significantly. Similarly, greenhouse dryers utilize the greenhouse effect to trap solar energy within an enclosed structure, enabling the drying process to continue even under low ambient radiation. According to Ayyappan and Mayilsamy (2021), greenhouse dryers exhibit enhanced drying rates and reduced product losses, especially during partially cloudy or windy conditions.

The thermal efficiency of any solar drying system is determined not only by its peak internal temperature but also by its ability to maintain stable drying conditions over time. Rapid fluctuations in chamber temperature or air velocity can lead to inconsistent drying, case hardening, or prolonged drying periods. Therefore, monitoring and analyzing real-time temperature, humidity, and airflow within these systems is essential for performance optimization. As Muthukumar and Venkatachalam (2020) observed in their thermal performance evaluation of solar dryers, fluctuations in drying conditions lead to non-uniform product quality, necessitating design improvements in airflow control and insulation.

Tomatoes, due to their high water activity and delicate cellular structure, require a drying environment that is both efficient and gentle. High temperatures may accelerate drying but can also result in nutrient loss, color degradation, and textural damage. Conversely, excessively slow drying may promote microbial activity and lead to fermentation or spoilage. Studies by Akpinar and Bicer (2020) emphasized that the ideal tomato drying system must maintain a drying temperature between 50°C and 65°C, ensuring sufficient moisture removal while preserving nutritional and sensory attributes. This balance is often difficult to achieve with open sun drying but can be more consistently managed in indirect and greenhouse systems, provided that proper thermal regulation mechanisms are employed.

Furthermore, crop-specific research is essential because the drying behavior of tomatoes differs significantly from other agricultural produce. Their high acidity, thin skins, and uneven internal moisture distribution make them particularly challenging to dry uniformly. Comparative studies, such as the one conducted by Ismail et al. (2018), showed that even slight modifications in air velocity or drying temperature can drastically affect the drying time and final quality of tomato slices. Therefore, it is insufficient to generalize the performance of solar dryers based on other crops. A focused experimental analysis tailored to tomato drying is necessary to generate valid, crop-specific performance metrics.

In the context of increasing climate variability and global emphasis on sustainable food systems, solar drying technologies present an opportunity to reduce dependency on fossil fuels and mitigate post-harvest food loss. The integration of solar dryers into rural agricultural systems offers not only environmental benefits but also economic and social advantages. Solar dryers operate without external power inputs, making them suitable for off-grid or energy-poor regions, while also reducing long-term operational costs compared to fuel-based drying alternatives. A study by Kumar and Tiwari (2022) emphasized that properly designed solar dryers can reduce drying time by more than 40% compared to open sun drying, with significant gains in product hygiene and market value.

Despite these potential advantages, adoption of solar drying systems remains limited, often due to a lack of accessible, comparative data on their performance. Many existing designs are not optimized for specific crops or regional climatic conditions, and users are often uncertain about the trade-offs between cost, complexity, and efficiency. According to Khoshtaghaza et al. (2019), farmers are more likely to adopt solar drying technologies when performance metrics such as drying rate, thermal efficiency, and product quality are demonstrated through real-time field experiments rather than simulations or generalized models. This highlights the need for localized, data-driven evaluations that account for material properties, meteorological variation, and economic feasibility.

Furthermore, this project provides a valuable educational platform within the field of Physics and Electronics. Designing and analyzing solar dryers helps to engage students with practical applications of thermodynamics, heat transfer, fluid dynamics, and sensor-based instrumentation. Integrating measurement tools for monitoring solar radiation, chamber temperature, and product weight during drying encourages a hands-on understanding of experimental physics and engineering design. As pointed out by Adeyanju and Bolaji (2020), such experimental projects foster critical thinking, problem-solving, and innovation of all essential skills in modern applied physics curricula.

The selection of tomatoes as the target crop further underscores the relevance of this study. Tomatoes are not only one of the most consumed vegetables globally but are also particularly sensitive to drying conditions. Their perishability, combined with widespread cultivation in Nigeria and other tropical countries, makes them a strategic focus for post-harvest technology development. By evaluating and comparing open sun, indirect, and greenhouse drying methods under the same environmental conditions, this research aims to identify which design offers the most efficient, cost-effective, and quality-preserving method for drying tomatoes.

The results will provide stakeholders including researchers, farmers, extension workers, and policy-makers with actionable insights to guide the adoption, improvement, and dissemination of solar drying technologies suited to tomato processing in regions with similar climatic and socioeconomic conditions.

1.2 Statement of the Problem

Tomato production plays a vital role in the agricultural economy of Nigeria and many developing nations, but its preservation remains a significant post-harvest challenge due to its high perishability and water content. It has been estimated that up to 45% of harvested tomatoes are lost before they reach the consumer, primarily due to inadequate preservation and inefficient post-harvest technologies (Olumekun & Akinoso, 2017). Open sun drying is the most accessible traditional method still widely used, but it is prone to contamination, weather disruption, and inconsistency in drying rates, often resulting in poor-quality dried products and significant economic losses (Adesina & Onwuka, 2020).

In response, various solar drying technologies have emerged, offering better environmental control and improved drying efficiency. However, these systems differ in their design, thermal behavior, and operational performance. Despite numerous innovations, there remains a lack of rigorous comparative studies that experimentally evaluate how direct (open sun), indirect, and greenhouse solar dryers perform under the same environmental conditions, especially when drying tomatoes. Most research focuses on individual dryer types, often under controlled laboratory settings, failing to reflect real field conditions (Kumar & Tiwari, 2022; Motevali et al., 2021).

This knowledge gap complicates the selection of the most efficient and appropriate drying method for specific crops and climates. Without a practical, side-by-side thermal analysis of solar dryers, local farmers and processors lack the data needed to make informed decisions about adopting low-cost, high-performance drying technologies. Consequently, there is a pressing need for a comparative thermal performance study that considers chamber temperature behavior, drying rate, and moisture loss during tomato dehydration, thereby providing reliable data for improved dryer selection, design, and usage in real-world agricultural contexts.

1.3 Aim of 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 tomato.

1.4 Objective 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 performances of the direct and indirect solar dryers by taking hourly measurement of the temperature in the chamber of the dryers.
- To take hourly measurement of the solar radiation
- To calculate the drying rate of the direct and indirect solar dryers through hourly measurement of the weight of the tomatoes.

- To carry out a comparative study of the thermal performance of the direct and indirect solar dryers.

1.4 Scope of the Study

This study is primarily focused on the design, construction, and comparative thermal analysis of three different tomato drying systems: direct sun drying (open sun), indirect solar drying, and greenhouse solar drying. It is limited to the drying of fresh tomato slices under naturally available solar radiation in a specific geographic location within Nigeria, characterized by tropical climatic conditions.

The research involves the fabrication of a direct solar dryer and an indirect solar dryer, while the greenhouse solar dryer is based on an already existing structure. Performance data were collected through hourly measurements of drying chamber temperatures, solar radiation intensity, and the moisture loss of tomato samples across each drying method.

The study is strictly confined to thermal performance evaluation, and does not include microbiological, economic, or long-term storage analysis. The scope also excludes computer simulations or modeling techniques, instead relying entirely on field-based experimental methods. The findings are intended to offer practical, evidence-based insights for small-scale farmers, food processors, and agricultural engineers seeking sustainable tomato drying solutions adapted to local environmental and economic conditions.

1.5 Justification of the Study

The justification for this study arises from the urgent need to reduce the high post-harvest losses of tomatoes in Nigeria and similar developing regions, where preservation methods are often inefficient or absent. Given that tomatoes are highly perishable and contain over 90% moisture, their spoilage rate is particularly high under ambient storage conditions (Olumekun & Akinoso, 2017). Open sun drying, the most common traditional method, exposes the produce to dust, pests, uneven heating, and weather variations, often leading to poor quality and contamination (Adesina & Onwuka, 2020).

By constructing and evaluating both indirect and greenhouse solar dryers in comparison with direct sun drying, this study provides a data-driven understanding of their thermal performance, specifically in terms of drying temperature, drying rate, and moisture loss. Such comparative analysis is necessary to recommend the most appropriate, cost-effective, and sustainable drying technology for local tomato farmers.

Additionally, this research serves academic relevance by integrating principles of thermodynamics, heat transfer, and instrumentation into real-world agricultural applications. As emphasized by Adeyanju and Bolaji (2020), experimental projects like solar dryer development foster applied physics learning while addressing community-level challenges. Thus, this study is justified both for its scientific merit and its socioeconomic potential to enhance food security through sustainable post-harvest practices.

CHAPTER TWO

LITERATURE REVIEW

At Modibbo Adama University of Technology, Yola, Hussein et al. (2017) constructed and tested a hybrid photovoltaic (PV) solar dryer. Their system integrated PV panels, a battery storage unit, and a solar collector, allowing operations under direct sunlight and during cloudy conditions using stored energy. In drying tomato slices, their hybrid system achieved a maximum temperature of 62°C and reduced moisture content from 94.2% to 10% within six hours, compared to nine hours in a non-hybrid dryer. The drying rate and efficiency were reported as 0.08 kg/h and 71%, respectively. The authors concluded that such systems are well-suited for remote, off-grid areas with limited electricity access.

Adejumo et al. (2023) designed and evaluated a hybrid solar dryer for processing cassava grates, integrating a solar collector, drying chamber, chimney, blower unit (with heater and fan), a solar panel, and a 12V DC battery. The study was carried out to assess the influence of drying temperature and cassava variety (TMS96/1414, TMS92/0326, and TMS01/1368) on moisture loss, drying rate, and efficiency. They reported that the dryer reached maximum drying chamber temperatures of 55°C for hybrid mode and 45°C for solar mode, where both are significantly higher than the ambient 26°C. Hybrid drying reduced the moisture content from 65% to approximately 10.19% in 7 hours, while solar drying required 13 hours to reach 11%, and open sun drying took 35 hours to achieve 13%. The researchers found that TMS92/0326 exhibited the highest moisture loss (6.20 kg/kg) and drying efficiency (up to 79.71%). Drying rates across the methods were 0.899 kg/hr (open sun), 0.870 kg/hr (solar), and 0.807 kg/hr (hybrid). They concluded that drying temperature, airflow rate, and cassava variety had significant effects on performance, with the hybrid solar dryer proving most efficient in achieving rapid and uniform drying of cassava grates.

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/m^2. 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.

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 Q_{pv} between 0.792–23.53% and Q_{col} 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.

Singh and Gaur (2021) developed a hybrid active greenhouse solar dryer integrated with an evacuated tube solar collector, specifically targeting the drying of high-moisture agricultural products such as tomatoes. They stated that the system included a heat exchanger where hot water heated by the solar collector is circulated through copper tubes, transferring heat to the surrounding air via convection and conduction. This setup produced higher internal chamber temperatures and enhanced the moisture removal rate. Tomato slices were dried from an initial moisture content of 94.6% (wet basis) to 10% within 10 hours. The authors estimated that the dryer could yield 261 kg of dried tomato annually, with an economic payback period of just 1.73 years. Furthermore, they calculated that over a projected lifespan of 30 years, the system would mitigate approximately 169.10 tonnes of CO_2, demonstrating both environmental sustainability and cost-effectiveness. They concluded that such a system is suitable for rural agricultural processing and is well-aligned with the principles of sustainable development.

Hossain et al. (2018) designed and evaluated a cabinet-type solar dryer in Bangladesh, featuring a collector area of 4.00 m² and a drying chamber area of 7.5 m², 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/m², with collector flux absorption at 103 W/m². 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 24.7for 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.

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.

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.

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.

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.

Samykano et al. (2023) investigated the performance of a single-basin, double-slope solar dryer utilizing natural convection for drying bottle gourds and tomatoes. The study aimed to present a sustainable, low-energy alternative to traditional open-sun drying, which is increasingly challenged by contamination risks and inconsistent weather conditions. The authors reported that their solar dryer achieved moisture reductions of 94.42% in tomatoes and 83.87% in bottle gourds, far outperforming open-sun drying. Drying air and plate temperatures reached 54.42°C and 63.38°C, respectively. Energy and energy efficiencies peaked at 68.5% for tomatoes and 61.78% for bottle gourds. The activation energy required for drying was significantly lower using the solar dryer: 29.14–46.41 kJ/mol for bottle gourds and 27.16–55.42 kJ/mol for tomatoes. The moisture diffusivity also showed substantial improvement, ranging between 3.12×10^{11} to 4.31×10^{11} m^2/s for bottle gourds and 2.31×10^{11} to 4.65×10^{11} m^2/s for tomatoes. An economic analysis indicated payback periods of 2 years for bottle gourds and 1.6 years for tomatoes. The researchers concluded that their system enhanced drying efficiency, preserved product quality, and aligned with sustainable post-harvest food processing goals.

Suherman et al. (2023) assessed the performance of a hybrid solar dryer for drying red chili pepper, comparing its efficiency to traditional sun drying and standard solar drying methods. The study independently tested drying air temperatures of 40°C, 50°C, 60°C, 70°C, and 80°C, evaluating temperature profiles, thermal efficiency, drying rate, energy behavior, and quality attributes such as color, vitamin C, and β-carotene content. The authors observed that the drying rate decreased with increasing temperature, while thermal chamber efficiency and drying effectiveness were inversely proportional to drying duration. The solar collector showed peak efficiency at 40°C, whereas energy and energy indicators increased with temperature. They confirmed that the hybrid dryer reduced moisture content to below 10.78%, meeting national standards. At 80°C, the dried chili retained desirable color values (L = 30.37, a = 27.45, b = 10.63), along with vitamin C content of 14.79 g/100 g and β-carotene content of 4.43 mg/100 g. The authors concluded that the hybrid solar drying method offered superior energy utilization, product quality, and thermal performance, making it an effective and sustainable option for chili drying.

King'ori and Simate (2024) investigated the drying performance and economic feasibility of a greenhouse solar dryer for small-scale tomato processing, comparing it with traditional open sun drying methods. The dryer system consisted of a steel frame structure, greenhouse-grade plastic covering, and a concrete floor. The authors conducted drying trials under natural weather conditions, with temperature and relative humidity monitored to assess their influence on drying efficiency. They reported that the greenhouse dryer achieved higher internal temperatures of 38.4°C on the first day and 45.5°C on the second day which facilitated a rapid moisture reduction to 14.9% (wet basis) within 11 hours. In contrast, open sun drying yielded only a reduction to 37.9% moisture under the same conditions, demonstrating the superior thermal performance of the greenhouse system. An economic analysis revealed a payback period of 1.6 years, indicating its investment attractiveness for smallholder farmers. The authors concluded that greenhouse solar drying technologies offer not only faster and more controlled drying but also financial viability, making them a promising strategy for value-added tomato processing in rural agricultural communities.

Yahya (2016) designed and evaluated the performance of a solar-assisted heat pump dryer integrated with a biomass furnace for drying red chillies, and assessed its drying kinetics. The study involved drying 22 kg of fresh red chillies, initially at a moisture content of 4.26 db, down to 0.08 db within 11 hours of operation. In contrast, open sun drying required 62 hours to reach comparable moisture levels, demonstrating an 82% reduction in drying time. The hybrid drying system maintained an average chamber temperature of 70.5°C, relative humidity of 10.1%, and air mass flow rate of 0.124 kg/s. The average drying rate, specific moisture extraction rate, and thermal efficiency were reported as 1.57 kg/h, 0.14 kg/kWh, and 9.03%, respectively. The study further evaluated three drying models of Newton, Henderson–Pabis, and Page to describe the drying kinetics, concluding that the Page model offered the best predictive accuracy, based on statistical metrics such as coefficient of determination (R^2), mean bias error (MBE), and root mean square error (RMSE). The author concluded that the solar-assisted hybrid dryer provided substantial time savings and consistent drying performance, and could serve as a reliable alternative to conventional sun drying.

Koua et al. (2017) experimentally investigated the thermal performance of an indirect forced convection solar dryer designed for drying cocoa beans. The system was composed of a solar collector, drying chamber, two fans, and an integrated photovoltaic power supply with battery storage. The researchers conducted experiments under three distinct meteorological conditions: sunny, partially cloudy, and cloudy. They observed that the temperature rise of the air inside the solar collector was 22.1°C on sunny days, 15.6°C on partially cloudy days, and 13.2°C on cloudy days, compared to the ambient temperature. The average solar radiation on the collector surface was measured as 644 W/m², 448 W/m², and 341 W/m², respectively. The thermal efficiency of the solar collector ranged between 34.89% and 43.40%, regardless of weather conditions, while the overall thermal drying efficiency of the system varied between 14.48% and 20.17%. They also reported that the temperature inside the drying chamber consistently exceeded ambient levels, demonstrating effective heat retention. The authors concluded that the dryer, supported by PV-powered airflow and battery storage, performed reliably across diverse weather conditions and offered a viable solution for efficient cocoa bean drying in tropical regions.Olatunbosun (2011) reported that the limitations associated with traditional open sun drying, including pest infestation, contamination, and poor hygiene, can be effectively addressed through the use of solar dryers. In his study on a domestic passive solar dryer constructed in Abeokuta, he developed a unit composed of a solar collector and a drying chamber fitted with three mesh trays. The dryer, constructed from locally available materials such as wood and polyurethane glass, achieved an internal temperature of 60.5°C—approximately 26°C higher than ambient conditions. He observed that moisture removal was significantly improved over conventional methods; for instance, cassava slices lost 199.9g of water in the solar dryer, compared to 156.8g using open sun drying. He concluded that passive solar drying provides a more hygienic and efficient alternative.

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.

In a study conducted in Kainji, Nigeria, Ogundana et al. (2022) designed and evaluated a solar dryer tailored to local meteorological conditions. Their dryer achieved an internal temperature of 74.5°C and demonstrated substantial improvements in drying efficiency over traditional methods. The study emphasized the importance of utilizing materials such as polyurethane glass and aluminum sheets to optimize thermal performance.

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.

Okeyode and Okuyelu (2023) evaluated a multifunctional electric-solar hybrid dryer used for drying cassava and red pepper. The dryer achieved moisture reductions of more than 84% and drying rates of up to 41.43 kg/hr at a drying temperature of 65°C. They reported a fabrication cost of only $260, making it affordable for small-scale farmers. The study concluded that such hybrid dryers are practical and cost-effective solutions.

Suherman et al. (2018) analyzed the drying efficiency of a solar tray dryer designed for cassava starch. Their experiments demonstrated a reduction in moisture content from 50% to 8% within a relatively short period. Internal dryer temperatures reached 60°C, while relative humidity dropped to 30%. The dryer achieved a thermal efficiency of 40%, reflecting its capacity to maintain a controlled drying environment.

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.

Silayo et al. (2015) examined cassava drying performance on various raised platforms. Their results showed that wire mesh surfaces yielded the best drying performance, significantly reducing drying time across different bed depths. The authors concluded that optimizing the surface material and bed depth could improve efficiency even in open drying scenarios.

Koleleni (2025) investigated the viability of passive solar dryers in food preservation. The dryer, constructed from wood and mild steel, reached internal temperatures over 75°C. It demonstrated drying rates nearly three times faster than open sun drying and maintained effective drying throughout the day. The study concluded that passive solar dryers are particularly advantageous for low-income communities with limited access to electricity.

Famurewa and Emuekele (2014) employed a fluidized bed dryer to study cassava drying under various air velocities and temperatures. Their statistical analysis showed that the Modified Henderson and Pabis model accurately described the drying kinetics of the cassava varieties tested. They concluded that fluidized bed drying provides a reliable basis for future dryer designs.

Hossain et al. (2023) developed a hybrid solar dryer combining a flat-plate concentrating collector, heat storage, and auxiliary heating for drying tomatoes. The dryer reduced 20 kg of fresh tomato halves to 4 kg of dried product, with efficiencies between 17–29%. Sodium metabisulphite (8g/L) pre-treatment inhibited microbial growth at temperatures below 45°C, though higher temperatures offered better color and nutrient retention. While minor losses of ascorbic acid, lycopene, and flavonoids were recorded, these were less than those in commercially dried tomatoes.

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.

In Zimbabwe, Kagande et al. (2012) designed a solar tunnel dryer that reduced tomato moisture content from 94.09% to 20.50% (dry basis) within 15 hours at air temperatures ranging between 32.6–56°C. Their findings showed that this US $500 system was cost-effective for smallholder farmers, producing high-quality dried tomatoes with minimal microbial contamination. The study emphasized the importance of temperature and airflow control, highlighting that solar tunnel dryers outperform open sun drying. They also stressed the need for rehydration to restore texture and recommended further investigation into nutritional losses due to different drying methods.

Chouikhi and Amer (2023) evaluated an indirect-mode forced convection solar dryer equipped with a photovoltaic/thermal (PV/T) air collector for tomato slice drying. The system simultaneously produced electricity and heated air. Computational fluid dynamics (CFD) validation showed a temperature variation of approximately 1°C in the collector and 2°C in the drying chamber. The average daily efficiencies recorded were 30.9% for the collector, 15.2% for the dryer, and 8.7% for the PV panel. The authors recommended 3D CFD modeling and prototype improvements for greater efficiency, and suggested future inclusion of mass transfer analysis.

Elshawadfy Elwakeel et al. (2024) assessed a tracking indirect solar dryer powered by photovoltaic cells. The study investigated drying kinetics at varying slice thicknesses (4–8 mm) and air speeds (1–2 m/s). Thicker slices extended drying time by up to 1.667 times. The tracking collector motion (TCM) outperformed fixed collector motion (FCM) in terms of higher internal temperatures and moisture diffusivity (9.30×10^{-10} m^2/s vs. 7.15×10^{-10} m^2/s). The modified Two-Term II model best described the kinetics with R^2 values of up to 0.99976. The system was also environmentally impactful, mitigating up to 6,795.4 tons of CO_2.

Vitouley et al. (2025) developed a forced-convection solar dryer for the 'Akikon' tomato variety in Benin. The drying time was halved from 1,266 to 672 minutes at temperatures between 55–70°C. While the system produced brightly dried tomatoes, color changes appeared after 7–8 months, indicating a need for improved packaging. The study recommended evaluating rehydration ability and shelf life for commercial application.

Hossain et al. (2023) developed a hybrid solar dryer combining a flat-plate concentrating collector, heat storage, and auxiliary heating for drying tomatoes. The dryer reduced 20 kg of fresh tomato halves to 4 kg of dried product, with efficiencies between 17–29%. Sodium metabisulphite (8g/L) pre-treatment inhibited microbial growth at temperatures below 45°C, though higher temperatures offered better color and nutrient retention. While minor losses of ascorbic acid, lycopene, and flavonoids were recorded, these were less than those in commercially dried tomatoes.

Aigbede et al. (2025) reviewed over 100 mathematical models for solar drying, identifying a gap in pineapple-specific models in Cotonou, Benin. Models such as Page and Wang and Singh were found most applicable for tomato drying. The study emphasized the need for localized models that optimize solar drying and minimize post-harvest losses. It also proposed a new heat balance model specifically adapted for indirect solar dryers.

Kulanthaisami et al. (2010) compared a solar cabinet dryer with open sun drying for tomato slices (4–8 mm) in Montreal, Canada. The cabinet dryer reduced moisture content from 94% to 11.5% in 300–570 minutes, compared to 435–735 minutes under OSD. The Page model best fit the drying behavior. Moisture diffusivity in the solar dryer ranged from 4.25×10^{-7} to 7.67×10^{-7} m^2/s, significantly higher than that in OSD. Solar-dried tomatoes had better color retention, rehydration ratio, and ascorbic acid levels.

Balogun et al. (2017) tested a double-compartment solar dryer in Nigeria, reducing tomato moisture from 90% to around 10.7% in two days, while OSD achieved only 25–42.9% in the same time. The solar dryer reached 58°C and an efficiency of 87.8%. The authors highlighted the dryer's capacity to protect tomatoes from contamination and environmental factors.

El-Mesery and Mao (2023) investigated infrared drying kinetics for tomato slices. Using radiation intensities of 0.14–0.35 W/cm² and air velocities of 0.5–1.5 m/s, they observed that higher radiation reduced drying time, while increased air velocity prolonged it. The Midilli model best described the drying behavior. Although infrared drying allowed for rapid moisture removal, its effects on nutritional content require further research.

2.1Working Principles of Indirect Solar Dryers

The indirect solar dryer functions through the principle of transferring heat generated by solar energy to the drying chamber without direct exposure of the crops to sunlight. In this system, solar radiation is first absorbed by a flat-plate solar collector, which is usually made of black-painted metal or absorber materials with high thermal conductivity. This collector heats the incoming ambient air, which is then directed into the drying chamber where the agricultural produce is placed on drying trays. The system is designed to ensure that heat transfer occurs efficiently through the mechanisms of conduction, convection, and radiation, all while minimizing heat losses through effective insulation and maximizing air exchange through inlet and outlet vents.

- Conduction: This in the indirect solar dryer occurs primarily through the metal absorber plate of the solar collector. When solar radiation strikes the blackened surface, it increases the thermal energy of the plate. This thermal energy is then conducted to the air flowing across or beneath the collector surface. The effectiveness of conduction depends on the thermal conductivity of the material and the temperature gradient established between the surface and the air. Materials like aluminum or galvanized iron are preferred due to their excellent thermal properties.

- Convection: Once the air is heated via conduction in the collector, natural or forced convection transports the warm air into the drying chamber. In passive systems, natural convection arises from the buoyancy of the warm air, causing it to rise and flow through the system. In active systems, fans may be used to increase airflow. As the hot air enters the chamber, it contacts the moist surfaces of the produce, absorbing moisture in the process. This heat transfer from hot air to produce is a classic example of convective drying, and the rate of drying depends significantly on airflow velocity, temperature, and relative humidity.
- Radiation: Although the drying chamber is not directly exposed to sunlight, radiation still plays a minor role in heating the internal surfaces of the chamber and the produce indirectly. The walls of the chamber may absorb some heat and re-radiate it as infrared radiation, contributing to warming the produce. However, this is less significant compared to conduction and convection in the indirect dryer.
- Insulation: To reduce heat loss and improve thermal efficiency, the collector and chamber are insulated using materials like glass wool, polystyrene, or foam boards. These materials minimize heat transfer to the surrounding environment, ensuring more of the collected thermal energy is directed toward drying. Proper insulation also helps maintain a stable internal temperature, which is crucial for consistent drying performance.
- Air Inlets and Outlets: The performance of an indirect solar dryer greatly depends on its air circulation system. The air inlet is typically located at the base or side of the collector to allow ambient air to enter and be heated. The outlet vents are located at the top or rear of the drying chamber to enable moisture-laden air to escape. Proper design of these vents ensures a continuous flow of air, preventing humidity build-up and allowing for

efficient moisture removal. In active systems, blowers or exhaust fans may be employed to enhance airflow and control drying rates.

2.1.1 Components of the Indirect Solar Dryer

An indirect solar dryer consists of several major parts:

- Solar collector: Captures and converts solar energy into heat.
- Drying chamber: Where the produce is arranged in trays, protected from direct solar radiation.
- Transparent glazing: Typically glass or clear plastic on the collector to trap solar radiation.
- Air ducts or passages: Direct the heated air into the drying chamber.
- Insulation: Maintains the internal temperature and reduces losses.
- Ventilation vents: Control airflow and moisture escape.

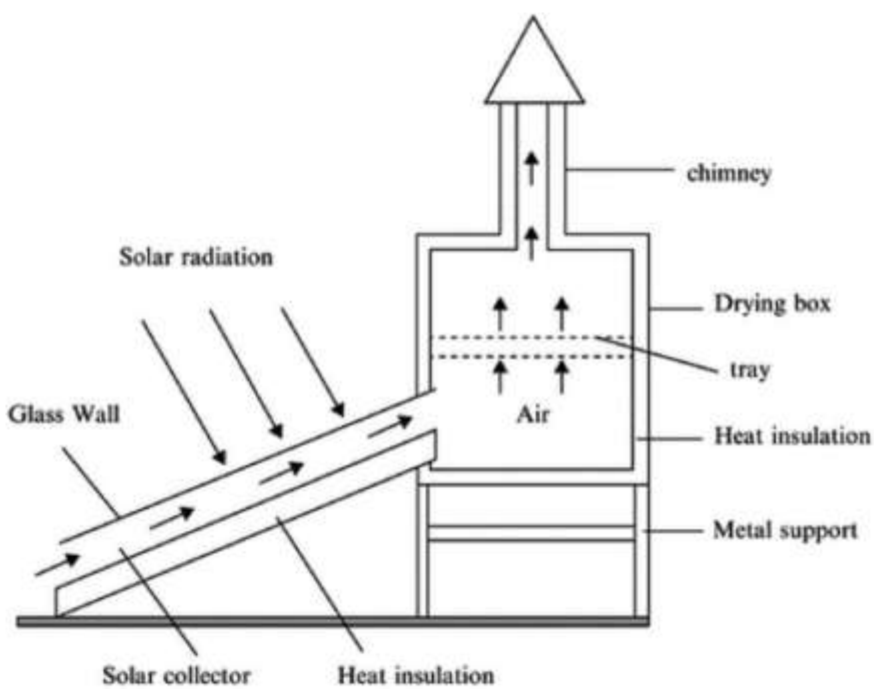

Figure 2.1.1: Labelled diagram of indirect solar dryer

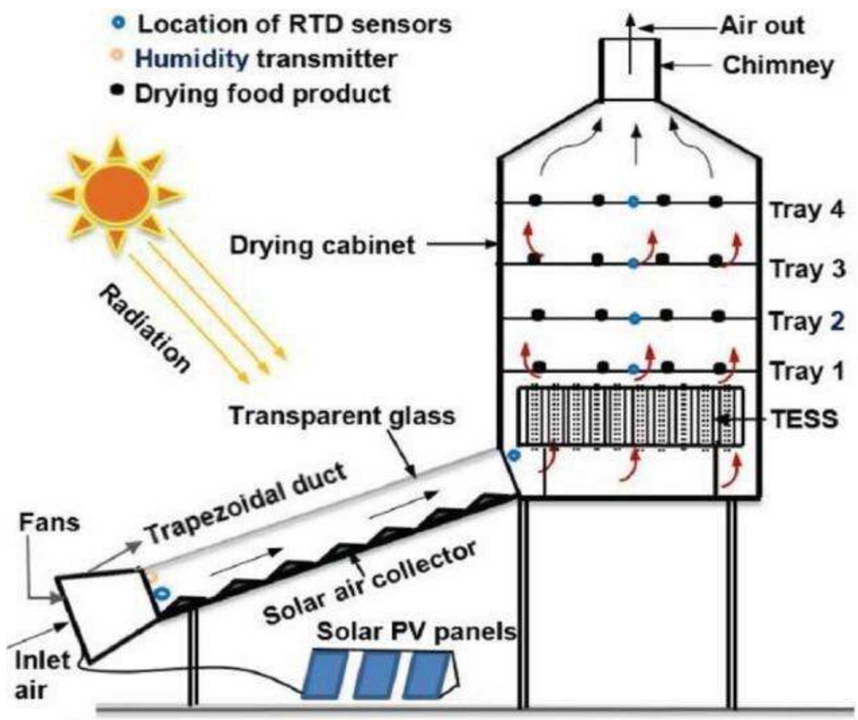

Figure 2.1.2: Labelled diagram of indirect solar dryershowing components and airflow.

2.2 Working Principle of Greenhouse Solar Dryer

The greenhouse solar dryer operates on the fundamental principles of solar energy conversion and heat transfer mechanisms namely radiation, conduction, and convection. This system utilizes a transparent or translucent covering material, usually polycarbonate, polyethylene, or glass, to allow the penetration of solar radiation into an enclosed drying chamber. Once inside, the radiation is absorbed by the interior surfaces and converted into thermal energy, which raises the ambient temperature within the chamber, facilitating moisture evaporation from the products placed inside. The greenhouse design ensures improved protection from environmental factors such as wind, rain, dust, and pests, while maintaining a relatively high and stable drying temperature. This system is suitable for a wide range of agricultural products, including fruits, vegetables, fish, meat, and spices.

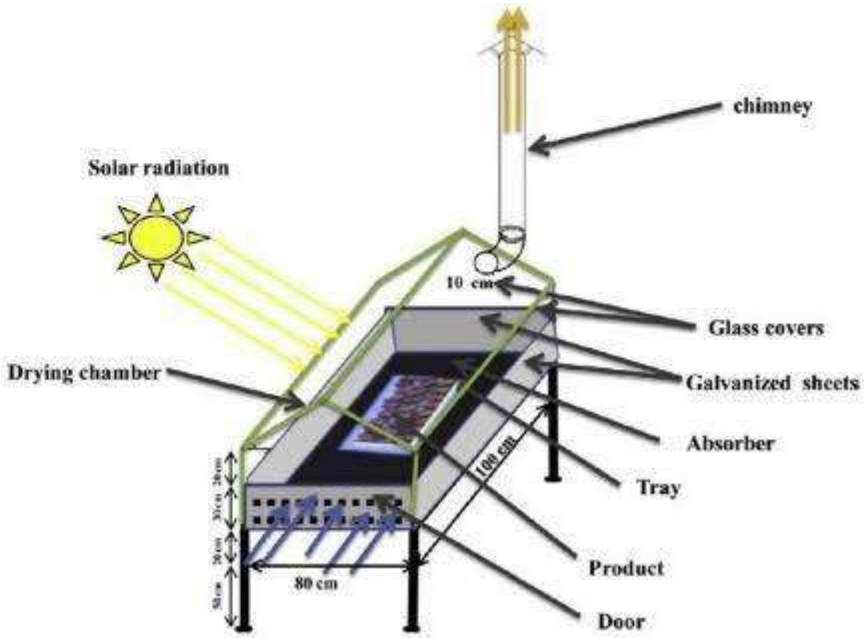

Figure 2.2.1: Schematic diagram of a typical greenhouse solar dryer

- Solar Radiation and Absorption: The primary energy input in a greenhouse dryer is solar radiation. Shortwave radiation from the sun passes through the transparent glazing material and is absorbed by dark-colored surfaces within the chamber typically the floor, tray supports, or specialized black absorber plates. These surfaces convert the radiant energy into heat, which then warms the air inside the dryer. According to Abubakar et al. (2021), up to 80% of the incoming radiation can be effectively trapped and utilized within a well-designed greenhouse dryer. The absorbed radiation raises the chamber temperature significantly above ambient, thus creating a conducive environment for efficient moisture evaporation.
- Conduction: This plays a role in transferring the absorbed heat from the dryer's surfaces to the product trays and ultimately to the agricultural

products. The absorber surface (e.g., black-painted metal or concrete floor) conducts heat to the drying trays through their physical contact or supporting frame. This heat transfer increases the temperature of the produce, which in turn enhances the rate at which internal moisture diffuses to the surface and evaporates. Thermal conductivity of the materials used in the floor and trays significantly influences the drying rate. Metallic frames and trays are often employed due to their superior conductive properties.

- Convection: Natural or forced convection facilitates the transfer of heat from the warm internal air to the surface of the drying product, and also aids in removing moisture-laden air from the system. As the interior air gets heated, it becomes less dense and rises, creating a natural convection current. Fresh ambient air enters through strategically positioned air inlets, replaces the moist air, and exits through outlets or ventilators located at the top or opposite end of the dryer. This airflow system ensures continuous removal of moisture vapor and maintains drying efficiency. In some designs, small DC fans powered by photovoltaic panels are used to enhance airflow (forced convection), particularly in larger greenhouse dryers (Azad et al., 2020).
- Radiation Trapping (Greenhouse Effect): One of the most defining principles of the greenhouse dryer is the radiation trapping mechanism. Incoming shortwave solar radiation passes through the transparent roof, but as the internal surfaces re-emit this energy as longwave infrared radiation, the glazing material becomes partially opaque to it, thereby trapping the heat inside. This phenomenon is known as the greenhouse effect and is critical to maintaining higher internal temperatures over long durations. As reported by Kumar and Tiwari (2019), internal temperatures in greenhouse dryers can exceed ambient temperatures by 15–30°C depending on weather conditions and design efficiency.

- Insulation: Thermal insulation is essential to minimizing heat loss and maintaining uniform temperature distribution. The base and side walls of the dryer are often insulated with materials such as polystyrene, foam boards, or insulating bricks to reduce conductive heat loss to the surrounding. Good insulation improves the thermal retention capacity of the system and contributes to energy efficiency. Additionally, air-tight sealing of joints and structural components helps prevent unintended convective losses (Sahu et al., 2020).

2.2.1 Components and Functions

A standard greenhouse solar dryer comprises several functional components:

- Transparent Roof or Covering: Usually made from UV-stabilized polyethylene or polycarbonate, this allows high solar transmissivity and aids in trapping heat via the greenhouse effect.
- Drying Trays: These are arranged in tiers for optimal space usage. Trays are often made from perforated metal or food-grade mesh to allow upward airflow.
- Absorber Base or Floor: Painted black to maximize solar absorption and made of high thermal mass materials to retain heat.
- Air Inlets: Located near the base of the dryer to draw in cooler, dry air from the environment.
- Air Outlets or Vents: Typically found at the top or rear, facilitating the expulsion of moist air and promoting air circulation.
- Supporting Frame: Constructed from wood, aluminum, or steel to support the structure and trays.

- Optional Fans and PV System: In hybrid systems, small solar-powered fans are added to enhance air movement, especially during cloudy weather.

The efficiency of a greenhouse solar dryer hinges on the synergy between these components. The drying process begins with solar radiation entering the system, which is absorbed and converted to heat. This heat is conducted to the drying products and convected around the chamber, while the greenhouse effect ensures thermal retention. Simultaneously, moisture evaporated from the products is carried away by airflow, completing the drying cycle. This integrated mechanism allows the greenhouse solar dryer to function effectively even in marginal weather conditions, offering superior product quality, reduced drying times, and protection from contaminants.

2.3 Classification of Solar Dryers

Solar dryers can be broadly classified based on design configuration, mode of air circulation, and energy source. However, the most common classification scheme distinguishes solar dryers into passive and active systems. These categories further branch into subtypes such as direct, indirect, and mixed-mode dryers. Each system possesses unique structural and functional characteristics that influence drying efficiency, heat transfer dynamics, airflow control, and suitability for specific crops and regions.

2.3.1 Passive Solar Dryers

Passive solar dryers operate without external mechanical energy input for airflow, relying solely on natural convection driven by solar heating and buoyancy forces. These systems are often simpler, cheaper, and easier to construct and maintain, making them highly suitable for small-scale rural farmers.

- Direct Passive Solar Dryers: In direct passive dryers, the product is placed in an enclosed chamber with a transparent cover (often glass or UV-treated polycarbonate) that allows solar radiation to strike the product surface directly. The drying chamber traps heat through the greenhouse effect, raising internal temperature and accelerating moisture evaporation (Esper & Mühlbauer, 1998). While this method enhances drying speed compared to open sun drying, the direct exposure of crops to sunlight can degrade color, nutrients, and aroma in sensitive produce such as tomatoes or herbs.Typical components include:Transparent cover for solar gain, vented walls for moisture-laden air escape, Drying trays or racks for product placement, Air inlet and outlet ports for passive airflow. These systems are best suited for products that tolerate or benefit from direct sun exposure.
- Indirect Passive Solar Dryers: In contrast, indirect passive dryers use a separate solar collector to heat air, which is then directed into a drying chamber housing the product. The drying air absorbs moisture from the product without exposing it to direct sunlight, thus preserving color, flavor, and nutritional value (Sodha et al., 1985). The collector typically consists of a black-painted absorber surface beneath a transparent cover, enclosed in an insulated box to enhance thermal efficiency.Key features include:Solar air heater (collector), Insulated drying chamber with trays, Natural convection vents for airflow, No external fan or electricity. These systems are particularly useful for drying heat-sensitive crops such as vegetables, spices, or medicinal plants, offering improved hygiene and reduced contamination risks.
- Mixed-Mode Passive Dryers: This combine direct and indirect drying principles. In this setup, the drying chamber receives heat both from direct solar radiation and from preheated air from a solar collector. This

configuration enhances drying efficiency and reduces drying time while minimizing the downsides of prolonged direct exposure (Bala, 2020).

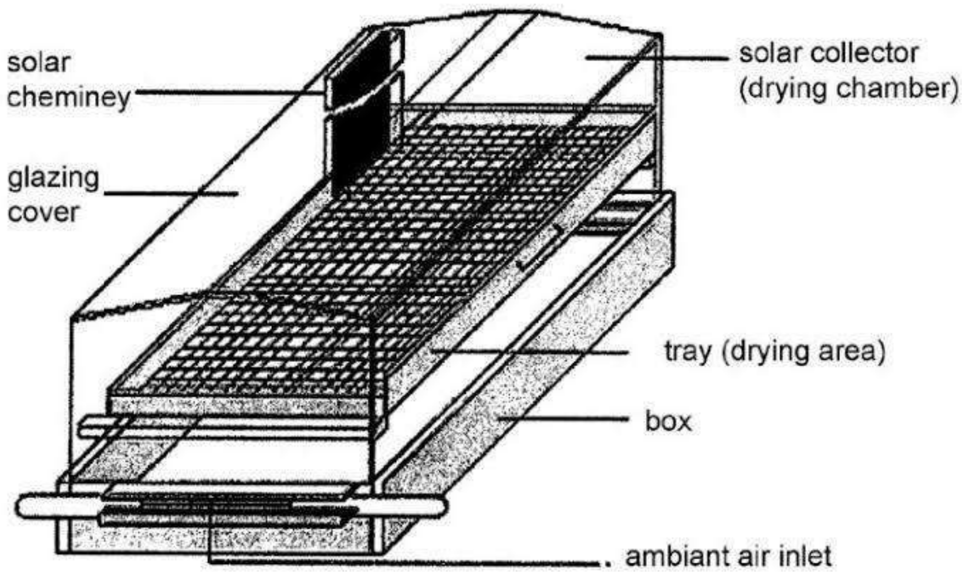

Figure 2.3.1: Layout of a Direct Passive Solar Dryer

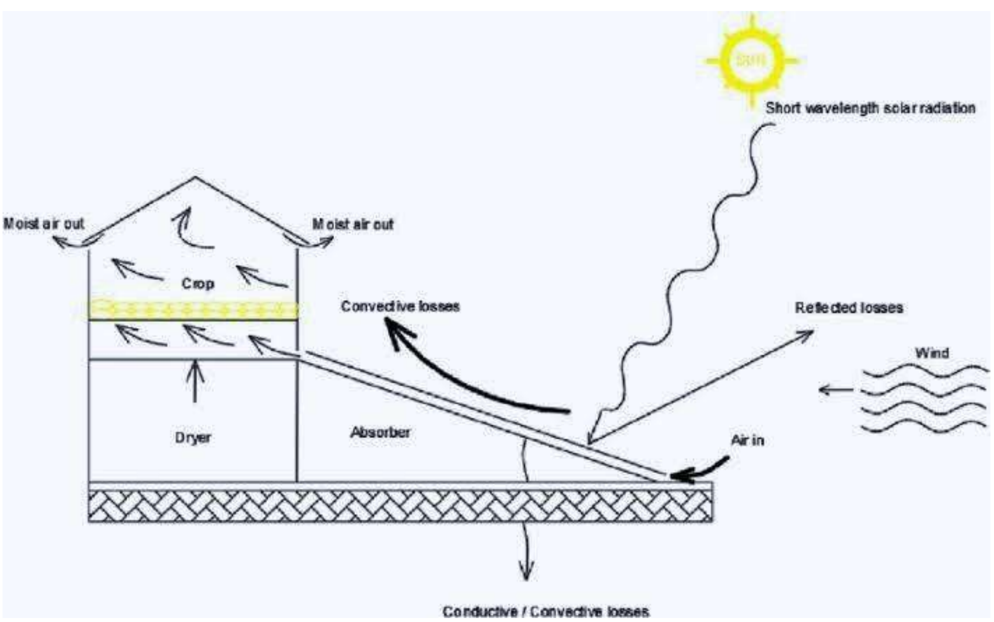

Figure 2.3.2: Layout of an Indirect Passive Solar Dryer

2.3.2 Active Solar Dryers

Active solar dryers incorporate mechanical systems such as fans or blowers powered by electricity or photovoltaic panels to regulate airflow and enhance heat distribution within the system. These dryers are more effective for large-scale or commercial drying operations due to their ability to maintain constant airflow, uniform temperature, and faster drying cycles regardless of ambient conditions.

- Direct Active Solar Dryers: In direct active systems, fans circulate hot air across the product while it is exposed to direct sunlight. Though similar to direct passive dryers in design, the mechanical airflow improves drying rate and uniformity. However, careful regulation is required to avoid nutrient degradation or over-drying (Sharma et al., 2009).
- Indirect Active Solar Dryers: These dryers use mechanical fans to force air through the solar collector and drying chamber. The forced airflow promotes turbulent mixing, enhancing heat and mass transfer. Because products are not exposed to direct radiation, indirect active dryers are well suited for high-value, perishable crops like fruits, vegetables, and medicinal plants.Components typically include:Solar collector (flat plate or concentrator), Drying chamber (insulated, multi-tiered), Electric or solar-powered fans, Thermostatic control (optional)
- Hybrid or Mixed-Mode Active Dryers: This combine solar and auxiliary energy sources (e.g., biomass burners or electrical heaters) to ensure continuous drying under cloudy conditions or at night. This versatility makes them suitable for industrial or year-round applications (Fudholi et al., 2014).

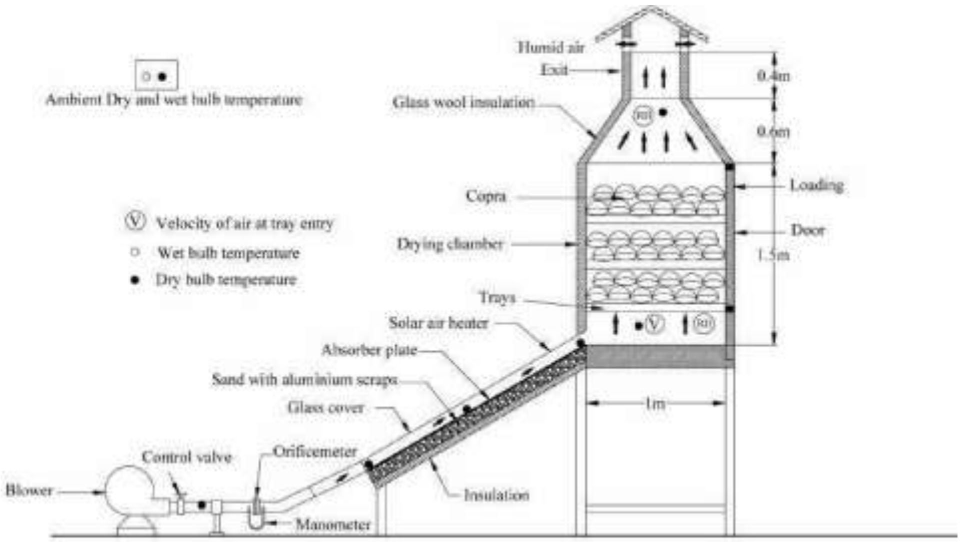

Figure 2.3.3: Layout of an Indirect Active Solar Dryer system

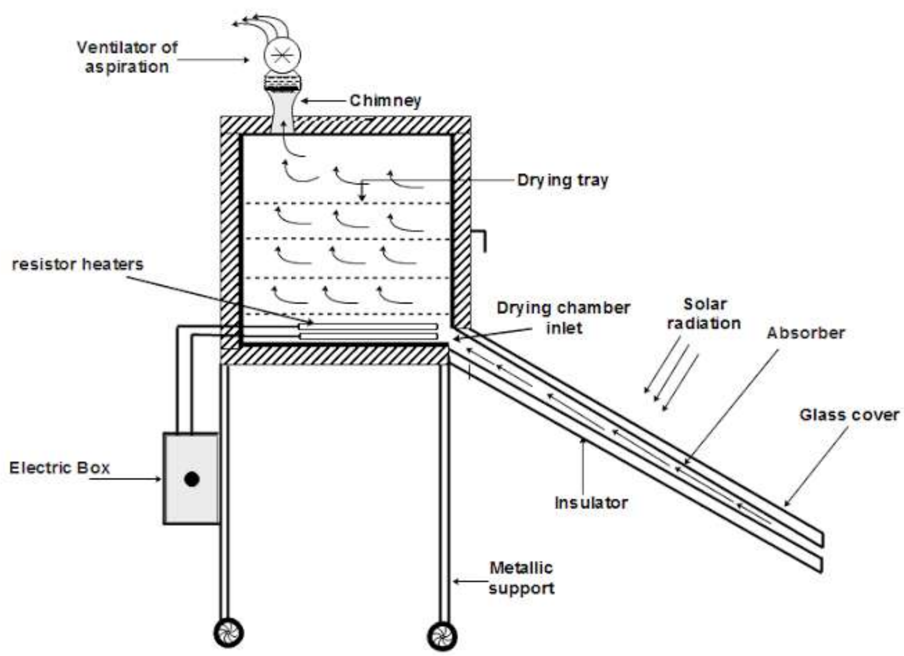

Figure 2.3.4: Layout of Hybrid Solar Dryer

Each classification serves different needs based on crop type, environmental conditions, user preferences, and resource availability. For instance, while passive dryers offer low-cost, eco-friendly solutions for rural farmers, active dryers provide higher throughput and precision drying required in commercial operations. The choice of dryer influences not only the thermal performance and drying rate, but also the nutritional and organoleptic quality of the dried product, which is central to the current research on the comparative performance of direct sun drying, indirect, and greenhouse solar dryers.

2.4 Solar Drying and Its Relevance

Solar drying represents a sustainable and energy-efficient method for preserving agricultural produce, utilizing the sun's radiant energy to reduce moisture content in crops. This process significantly minimizes microbial growth and enzymatic activity, which are primary causes of postharvest spoilage. In many tropical and subtropical regions, traditional open sun drying has been a common preservation method. However, it is often constrained by uncontrollable environmental factors such as rain, wind, pests, dust, and uneven drying, which can degrade product quality (Esper & Mühlbauer, 1998; Bala, 2020).Modern solar drying technologies such as direct, indirect, and greenhouse solar dryers have emerged to address these limitations, offering controlled drying environments that improve drying efficiency, reduce contamination, and ensure uniform product quality. These systems also help farmers reduce postharvest losses and increase income by preserving surplus produce for future sales or processing (El-Sebaii & Shalaby, 2012). In regions lacking access to electricity or other fuel sources, solar dryers serve as cost-effective, low-maintenance alternatives that contribute to food security and environmental conservation.The relevance of solar drying extends beyond its technical benefits to its alignment with global sustainability goals. By replacing fossil-fuel-dependent drying systems, solar dryers reduce greenhouse gas emissions and reliance on non-renewable energy sources. Furthermore, solar dryers can be designed to accommodate a wide variety of crops including tomatoes, peppers, fish, cassava, and herbs making them adaptable for small- and medium-scale farmers in diverse climatic zones (Forson et al., 2007; Fudholi et al., 2014).The growing emphasis on cleaner technologies and rural development has heightened the importance of solar drying in agricultural value chains. This makes it a vital component in postharvest technology, especially in sub-Saharan Africa and other regions where energy access is limited and food preservation remains a challenge.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Construction Materials for the Solar Dryers

- High-density fiber (HDF) plywood boards: were used to form the outer casing of the indirect solar dryer, covering the sides and base of both the drying chamber and the solar collector. This material was chosen due to its smooth finish, ease of cutting, and moderate thermal resistance, which helped reduce heat loss from the system. HDF is also cost-effective and locally available, making it suitable for low-resource settings. When properly sealed or painted, it offers decent durability and structural support for enclosing the dryer while maintaining a clean, professional appearance.

- Transparent glass: was used as the glazing material for the solar collector in the indirect dryer and for enclosing the entire structure of the greenhouse dryer. Its primary role was to allow solar radiation to penetrate into the system while trapping long wave heat through the greenhouse effect. Glass was chosen over plastic alternatives due to its superior clarity, durability, and resistance to UV degradation. In the indirect dryer, a combination of 10mm inner and 5mm outer glass was used to enhance insulation, reduce heat losses, and maintain structural integrity under outdoor exposure.

- Black-painted metallic iron sheets: were used as the absorber within the solar collector of the indirect dryer. Their function was to absorb incoming solar radiation and convert it into heat, which in turn raised the temperature of the air within the collector. The black coating increased the surface's ability to absorb solar energy by minimizing reflectivity, while the metal's high thermal conductivity allowed for efficient heat transfer to the passing air. This combination enhanced the overall thermal performance of the dryer.

- Fiber material: was used as insulation within the walls of the indirect solar dryer to minimize heat loss. It was placed between the inner and outer layers of the dryer's structure to prevent thermal conduction from the heated interior to the cooler external environment. Fiber was selected because of its low thermal conductivity, lightweight nature, and ease of installation. This helped maintain higher internal temperatures, improved drying efficiency, and reduced fluctuations caused by external weather conditions.
- Drying Trays: Instead of wire mesh, plastic trays were used to hold the pepper samples. These trays were wrapped with aluminum foil to enhance hygiene and reflectivity, minimizing contamination and improving drying surface conditions.
- Angle iron: was used to construct the metallic stand for the indirect solar dryer. It provided strong structural support for both the collector and the drying chamber, ensuring the entire unit was elevated and stable. The use of metal offered durability and resistance to bending or warping under load or prolonged sun exposure.
- Aluminum angle: was used to seal exposed gaps along the edges of the solar collector in the indirect dryer, particularly where the glass met the wooden or metallic frame. Its purpose was to prevent rainwater from seeping into the collector during wet conditions and to reduce heat loss through structural joints. Aluminum was chosen for this sealing role due to its corrosion resistance, ease of bending, and durability in outdoor environments. This helped maintain the integrity of the collector and ensured consistent thermal performance.

- 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.

- 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.

- 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 Instruments Used

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

- Digital Multimeter with Sensor Probe Model DM8100: 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 3.2.4 Digital Weighing Scale

3.3 Construction Process

The construction process commenced with meticulous planning and detailed design schematics to guide the fabrication of both the indirect and greenhouse solar dryers. Accurate dimensional measurements were taken to ensure that each component would align properly during assembly.

For the indirect solar dryer, the solar collector was constructed using a flat metallic plate measuring 123 cm in length, 57 cm in breadth, and 21 cm in height. This plate functioned as the primary absorber of solar radiation, intended to heat the incoming air before it passed into the drying chamber. The drying chamber (cabinet), designed to house the produce trays, was built with a length of 85 cm and a breadth of 52.5 cm.At the upper rear section, a chimney was installed and slightly tilted to permit rainwater drainage. The chimney components were fabricated with the following dimensions:

- Chimney back: 38 cm × 28.5 cm
- Chimney sides: 20.5 cm × 38 cm
- Chimney head: 28.5 cm (length) × 33 cm (breadth) × 12.5 cm (height)

An access door measuring 72 cm in length and 67 cm in breadth was incorporated into the drying cabinet to allow easy handling of trays and inspection of the drying process.

Figure 3.3.1 during welding process of the indirect solar dryer

The frame components, including the collector plate and structural elements, were transported to a local welding workshop located in GRA, Ilorin, behind the Governor's Office. Welding was carried out under close supervision to ensure strict adherence to the specified dimensions and design.

Figure 3.3.2 welded framework of the indirect solar dryer

Upon completion, the assembled frame was returned to the department and painted using automobile-grade black paint to enhance solar absorption. After the paint dried, the entire unit was mounted on a decking platform behind Physics Laboratory A, selected for its elevation and lack of shading obstructions. A ladder was used to transport and position the dryer on the platform.The structural casing was constructed using High-Density Fibreboard (HDF) plywood, which was used to enclose the dryer's sides. The top portion of the collector was covered with transparent glass to allow sunlight penetration. Two glass layers were installed:

- Inner layer: 10 mm thick
- Outer layer: 5 mm thick

The edges were sealed using aluminum angles, while rubber lining was added to prevent water ingress during rainfall. Additionally, hinges, handles, and locks were installed to facilitate ease of access and improve operability. The assembly process involved the use of nails, screws, and hammers to ensure structural integrity. Following completion, the entire unit was thoroughly cleaned, both internally and externally.

Figure 3.3.3 completed construction of the indirect solar dryer

Work was also undertaken on an existing greenhouse solar dryer, which required repairs to restore its operational integrity. The main structural dimensions of the greenhouse dryer were:

- Overall body: 154.5 cm (length) × 104.5 cm (breadth) × 100 cm (height)
- Raised head section: 104.5 cm (length) × 55 cm (breadth) × 49.5 cm (height)

A new collector plate was fabricated and installed, measuring 149 cm in length and 102 cm in breadth. Repair work included replacing broken glass panels and rebuilding the door. After repairs, the entire unit was cleaned, reassembled, and prepared for experimental use.

Figure 3.3.4 completed construction of the greenhouse solar dryer

Both the indirect and greenhouse solar dryers were mounted side by side on the same elevated platform and aligned in the same direction to ensure uniform solar exposure during testing. This strategic placement helped to maintain consistent environmental conditions and optimize performance comparison between the two systems throughout the experimental period.

3.4 Experimental Setup

The experimental setup began with the preparation of our sample fresh tomatoes (Solanum lycopersicum) used for the drying process. The tomatoes were purchased from Mandate Market in Ilorin and then brought to the laboratory for preparation. The tomatoes were washed with clean water to remove any surface contaminants. After washing, the stems were removed, and each tomato pod was carefully 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 tomato after loading. The sliced tomato 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 tomato slices. The actual weight of the tomato was obtained by subtracting the tray-and-foil weight from the total weight. These trays were then placed inside their respective drying systems, 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: Tomatoes 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 9:00 am to 5:00 pm daily, across a three-day 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 tomato 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 tomato slices 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, moisture removal capacity, and drying performance under real environmental conditions.

3.5 Performance Evaluation Parameters

To assess the effectiveness of the solar dryers used in this research, which are greenhouse solar dryer, indirect solar dryer, and open sun drying. Several thermal and physical parameters were calculated. These parameters help in understanding the drying behavior, energy utilization, and efficiency of the systems. The main parameters considered include moisture content, drying rate, and thermal efficiency.

- Moisture content: This is a critical parameter in drying studies, as it reflects the amount of water present in the product at any given time. It determines the quality and shelf-life of dried products. During drying, the moisture content decreases progressively until it reaches a level safe for storage. Inadequate drying can lead to microbial growth, spoilage, and loss of quality, while over-drying may reduce nutrient content and increase energy usage. In this research, the moisture content was calculated on a wet basis, which is more common in food processing studies. The formula used is:

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

$$M_i = Initial\ Weight$$

M_f = Final Weight

This formula provides the moisture removed relative to the original weight of the material. For each drying method, weights were recorded hourly, and the reduction in mass was used to compute the moisture loss throughout the drying period. Accurate determination of moisture content is essential for comparing the drying performance of different systems. This approach is widely used in solar drying studies, particularly in agricultural products like cassava, tomatoes, and peppers (Mohammed et al., 2021; Bala, 1997; Onuoha & Obetta, 2010).

- Drying rate: This is another essential parameter that indicates the speed at which moisture is removed from a substance. It helps in understanding the drying kinetics and how efficiently the solar dryer performs over time. A higher drying rate suggests faster moisture removal, better thermal performance, and reduced drying time, all of which contribute to energy savings and product quality. It is measured in grams per hour (g/h) or kg/h and expressed as:

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

$$M_i = \ Initial\ Weight$$

$$M_f = \ Final\ Weight$$

$$T = \ Time\ interval\ in\ Seconds$$

For Wet Basis:

$Drying\ Rate = \frac{M_i - M_f}{T} \times 100$

The drying rate gives insights into the drying behavior at each stage. For example, drying is usually faster in the initial stage when the moisture content is high and slows down as the product loses moisture. These trends were carefully observed and calculated during the Eight-day experimental period in this study. A steady or high drying rate usually reflects good heat and mass transfer characteristics of the dryer (Hossain & Bala, 2007; Janjai & Bala, 2012). By comparing drying rates across the greenhouse, indirect, and open sun drying methods, one can determine which system achieves quicker drying with minimal nutrient and quality loss.

- Thermal efficiency (or drying efficiency): This is a measure of how well the solar dryer converts incident solar energy into useful energy for moisture removal. It reflects the effectiveness of the system in utilizing available solar radiation to generate heat that facilitates drying. The thermal efficiency was calculated using the formula:

$$\eta_{cdg} = \frac{\dot{M} \quad C_{pa}(T_i - T_O)}{A_c I_g} \qquad Where:$$

$$C_{pa}: Specific\ Heat\ Capacity\ of\ Air$$

$$M\ : Mass\ of\ Sample$$

$$T_i\ : Collector\ Temperature$$

$$T_O : Ambient\ Temperature$$

$$I_g : Global\ Solar\ Radiation$$

$$A_c : Area\ of\ the\ collector$$

This equation helps determine how much of the captured solar energy was used in evaporating moisture from the product. A higher efficiency indicates a better-performing solar dryer with minimal energy losses. The efficiency is affected by several factors, including the design of the collector, insulation, airflow, ambient temperature, and solar intensity. For this study, efficiency values were calculated for both the indirect and greenhouse dryers using the recorded solar radiation and moisture loss data. Solar radiation was measured hourly using a pyranometer or solar meter, and temperature data helped in validating thermal performance.

This method is frequently adopted in solar drying literature (Bukola & Ayoola, 2008; Janjai & Bala, 2012) and serves as a benchmark to compare the performance of different solar drying systems.

3.6 Sample Calculations using the experimental Data (Day1- Day 6)

Calculation of Moisture content of Tomato

Tray 6- Greenhouse (Day 1)

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

Initial weight M_i = 612g

Final weight M_f= 287g

- Time: 11:30am

$$Moisture\ Content = \frac{612 - 287}{287} = 1.132g$$

- Time : 12:30pm

$$Moisture\ Content = \frac{580 - 287}{287} = 1.020g$$

Tray 5- Open Sun Drying (Day 1)

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

Initial weight M_i = 598g

Final weight M_f= 311g

- Time: 11:30am

$$Moisture\ Content = \frac{598 - 311}{311} = 0.922g$$

- Time: 12:30pm

$$Moisture\ Content = \frac{570 - 311}{311} = 0.832g$$

Tray 1- Indirect (Day 1)

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

Initial weight M_i = 655g

Final weight M_f= 310g

- Time: 11:30am

$$Moisture\ Content = \frac{655 - 310}{310} = 1.112g$$

- Time : 12:30pm

$$Moisture\ Content = \frac{645 - 310}{310} = 1.080g$$

Calculation of Drying Rate

Tray 1 – Indirect (Day1)

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

Initial Weight = 655g

Final Weight = 310g

- Time : 11:30am

$$Drying\ Rate = \frac{655 - 310}{60 \times 60} = 0.095g \quad = \frac{655 - 310}{3600} \times 100 = 9.5\%$$

- Time : 12:30pm

$$Drying\ Rate = \frac{645 - 310}{60 \times 60} = 0.093g \quad = \frac{645 - 310}{3600} \times 100 = 9.3\%$$

Tray 6 – Greenhouse (Day1)

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

Initial Weight = 612g

Final Weight = 287g

- Time : 11:30am

$$Drying\ Rate = \frac{612 - 287}{60 \times 60} = 0.902g \qquad = \frac{612 - 287}{3600} \times 100 = 90.2\%$$

- Time : 12:30pm

$$Drying\ Rate = \frac{580 - 287}{60 \times 60} = 0.813g \qquad = \frac{580 - 287}{3600} \times 100 = 81.3\%$$

Tray 5 – Open Sun Drying (Day 1)

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

Initial Weight = 598g

Final Weight = 311g

- Time : 11:30am

$$Drying\ Rate = \frac{598 - 311}{60} = 4.78g \qquad Drying\ Rate = \frac{598 - 311}{60\ \times 60} = 0.079g$$

- Time : 12:30pm

$$Drying\ Rate = \frac{570 - 311}{60} = 4.31g \qquad Drying\ Rate = \frac{570 - 311}{60\ \times 60} = 0.071g$$

Efficiency Calculation

Tray 1 – Indirect (Day 1)

$$\eta_{cdg} = \frac{m\ C_{pa}(T_i - T_o)}{A_c I_g}$$

Where;

C_{pa} : Specific capacity of air (1.005J/g/ ^{o}C)

I_g : Global solar radiation

T_i : Temperature of the collector

T_o : Ambient temperature

m : Mass of the sample

A_c : Area of the collector (area of the cube)

Where;

w = 57cm = 0.57m

h = 21cm = 0.21m

l = 123cm = 1.23m

$$A = 2(lw + wh + lh)$$

$$A = 2(1.23 \times 0.57 + 0.57 \times 0.21 + 1.23 \times 0.21)$$

$$A = 2(0.7011 + 0.1197 + 0.2583)$$

$$A = 2(1.0791)$$

$$A = 2.1582 \approx 2.16m^2$$

- Time : 09:40am

$$\eta_{cdg} = \frac{m\, C_{pa}(T_i - T_o)}{A_c I_g} = \frac{655 \times 1.005(36.2 - 27.4)}{2.16 \times 453} = 5.9202$$

- Time : 10:40pm

$$\eta_{cdg} = \frac{m\, C_{pa}(T_i - T_o)}{A_c I_g} = \frac{645 \times 1.005(48.7 - 34.5)}{2.16 \times 641} = 6.648$$

Tray 6 – Greenhouse (Day 1)

$$\eta_{cdg} = \frac{m\, C_{pa}(T_i - T_o)}{A_c I_g}$$

Where;

C_{pa} : Specific capacity of air (1.005J/g/ ^{o}C)

I_g : Global solar radiation

T_i : Temperature of the collector

T_o : Ambient temperature

m : Mass of the sample

A_c : Area of the collector (area of the cube)

Where;

$$A = l \times b$$

l = 1.49m

b = 1.02m

$$A = 1.49 \times 1.02$$

$$A = 1.52m^2$$

- Time : 11:30am

$$\eta_{cdg} = \frac{m\ C_{pa}(T_i - T_o)}{A_c I_g} = \frac{612 \times\ 1.005(28.4 - 27.4\ )}{1.52 \times 453} = \frac{615.06}{688.5} = 0.893$$

- Time : 12:30pm

$$\eta_{cdg} = \frac{m\ C_{pa}(T_i - T_o)}{A_c I_g} = \frac{580 \times\ 1.005(41.2 - 34.5)}{1.52 \times 641} = \frac{3905.43}{974.32} = 4.008$$

CHAPTER FOUR

4.0 RESULT AND DISCUSSION

This study rigorously evaluated the effectiveness of various solar drying systems for dehydrating tomatoes, with the primary objective of identifying the most efficient method while simultaneously highlighting the distinct advantages associated with each drying technique employed. Over a span of six days, an initial sample of 655g of tomatoes was reduced to 324g using an indirect solar dryer. In comparison, a greenhouse solar dryer effectively decreased a 612g sample of tomato to 287g, while open-air drying resulted in a reduction of 598g of tomato to 311g. The parameters measured during these experiments included (a) solar radiation incident on the collector, (b) ambient temperature, (c) temperatures within the drying chambers of both the indirect and greenhouse solar dryers, (d) collector temperature in the indirect solar dryer, (e) ambient humidity levels, (f) moisture content of the dried product, and the overall drying rate, adhering to the international standards established by ASABE/ASAE (2007) for solar air collectors. Temperature measurements were conducted at various points within the collectors and chambers utilizing a K-type thermocouple multimeter, with the drying regimen commencing daily at 8:00 AM and concluding at 4:00 PM, 4:30PM, 5:00PM, and 5:30PM respectively.

CHAPTER FIVE

5.0 CONCLUSION

This study was carried out to design, construct, and evaluate the comparative performance of three different drying methods which are open sun drying, an indirect solar dryer, and a greenhouse solar dryer for preserving tomato. The primary goal was to assess which of the systems provides the most efficient and effective drying conditions in terms of moisture removal, temperature stability, and overall performance.

The experimental procedure involved drying tomato slices under each of the three systems, with hourly measurements taken for temperature, humidity, solar radiation, and sample weight across several days. The performance of each system was evaluated based on moisture content reduction, drying rate, and thermal efficiency.

From the data obtained, it was observed that the greenhouse solar dryer consistently recorded the highest internal temperature, followed closely by the indirect solar dryer, while direct sun drying (open sun) showed the lowest and most fluctuating temperature values. These temperature patterns had a direct impact on drying performance. The greenhouse dryer achieved the fastest moisture reduction, indicating a more stable and controlled drying environment. The indirect dryer also showed improved performance compared to open sun drying, particularly in maintaining hygiene and reducing contamination risks. In terms of drying efficiency, both the greenhouse and indirect systems outperformed the open sun method, demonstrating the advantage of using structured drying systems in minimizing spoilage, improving drying speed, and preserving nutritional quality.

The findings from this project confirm that incorporating engineered solar dryers particularly the greenhouse and indirect type can significantly improve the drying of tomato, contributing to better post-harvest handling, reduced losses, and improved product quality. The results encourage the adoption of such systems among local farmers and food processors, especially in rural areas where electricity is not readily available.

5.1 RECOMMENDATIONS

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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