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Design, Development, and Performance Evaluation of an Improved Indirect Solar Mango Dryer for Sustainable Post-Harvest Preservation in The Gambia

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Abstract

Post-harvest losses of fresh mangoes remain a significant challenge to food security, rural livelihoods, and agro-industrial development in The Gambia. During the annual mango harvesting season, substantial quantities of fruit are lost because of rapid deterioration, inadequate preservation technologies, limited access to reliable electricity, and dependence on traditional open-sun drying methods. Although solar drying offers an environmentally sustainable alternative, many existing cabinet dryers exhibit poor airflow distribution, excessive humidity retention, uneven drying, and mould formation, reducing product quality and limiting adoption by rural processors. This study presents the design, development, and engineering evaluation of an improved indirect natural-convection solar mango dryer specifically adapted to the climatic conditions of The Gambia. The proposed system integrates a high-efficiency solar air collector, an insulated drying chamber, food-grade removable trays, a balanced natural ventilation system, and a vertical chimney with an adjustable damper to improve airflow and moisture removal. The dryer is designed to process ***20–50 kg of fresh mango slices per batch****, operating within an optimal drying temperature range of* ***50–65°C*** *while maintaining continuous natural airflow. Engineering analyses include airflow modelling, chimney design, solar collector optimization, tray configuration, and material selection using locally available resources. The design emphasizes improved drying uniformity, reduced drying time, enhanced product quality, and effective prevention of mould development through controlled ventilation and moisture extraction. The proposed dryer provides a low-cost, energy-efficient solution suitable for smallholder farmers, cooperatives, and rural agro-processing enterprises. Beyond reducing post-harvest losses, the system contributes to renewable energy utilization, food security, rural income generation, and climate-resilient agricultural development in The Gambia. The study establishes a practical engineering framework for future prototype validation, performance testing, and commercialization of sustainable solar drying technologies for tropical fruit preservation across West Africa. The engineering design parameters and construction principles presented in this paper are derived from the prototype developed for research and field testing in The Gambia.*

Keywords: Indirect solar dryer; mango preservation; renewable energy; post-harvest losses; natural convection; agricultural engineering; food processing; sustainable agriculture; solar drying

1. Introduction

1.1 Background

Agriculture remains one of the most important sectors of the Gambian economy, providing employment, food, and income for a large proportion of the rural population. The sector contributes significantly to rural livelihoods and national food security, particularly among smallholder farming households (Food and Agriculture Organization [FAO], 2023; World Bank, 2024). Mango (*Mangifera indica* L.) is among the most widely cultivated fruit crops in the country and is grown extensively in the West Coast Region, Lower River Region, Central River Region, Upper River Region, and North Bank Region. The tropical climate of The Gambia, characterized by high solar radiation, warm temperatures, and a distinct rainy season, provides

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favorable conditions for mango production (FAO, 2023; Ministry of Agriculture, Livestock and Food Security [MoALFS], 2022). During the peak harvest period, however, the supply of fresh mangoes frequently exceeds local market demand, resulting in substantial post-harvest losses that reduce farmers' incomes and limit opportunities for value addition (Kader, 2005; FAO, 2023).

Fresh mangoes possess a high moisture content of approximately 80–85% and continue to respire after harvest, making them highly susceptible to physiological deterioration, microbial spoilage, and quality degradation if not preserved promptly (Bechoff et al., 2018; Yahia, 2019). In many rural communities across The Gambia, the absence of cold storage facilities, limited access to reliable electricity, inadequate transportation infrastructure, and insufficient agro-processing technologies contribute to significant losses before the fruit reaches consumers (World Bank, 2024; FAO, 2023). These post-harvest losses reduce household incomes, increase food waste, constrain agro-industrial development, and negatively affect national food security and economic growth (Gustavsson et al., 2011).

Solar drying has emerged as one of the most promising sustainable preservation technologies for tropical fruits because it utilizes abundant renewable solar energy while reducing dependence on fossil fuels and conventional energy sources (Esper & Mühlbauer, 1998; Bala, 2017). Compared with traditional open-sun drying, indirect solar drying provides improved product hygiene, protection against insects and dust, reduced microbial contamination, better color retention, and enhanced nutritional quality through controlled drying conditions (El-Sebaii & Shalaby, 2012; Bala, 2017). Nevertheless, many low-cost cabinet solar dryers used in developing countries experience poor airflow distribution, inadequate ventilation, excessive humidity accumulation, and uneven heat transfer, resulting in prolonged drying times, inconsistent product quality, and mould development (Fudholi et al., 2015; Jain & Tiwari, 2004). These engineering limitations reduce drying efficiency and discourage widespread adoption among smallholder farmers and rural agro-processors.

The improved indirect solar mango dryer developed in this study addresses these challenges by integrating optimized airflow management, an insulated drying chamber, a high-efficiency solar air collector, food-grade drying trays, and an enhanced natural-convection chimney system to improve heat transfer and moisture removal. The engineering design is specifically tailored to the climatic conditions of The Gambia and emphasizes the use of locally available construction materials and fabrication techniques that can be adopted by local artisans and small-scale enterprises. The proposed design aims to improve drying uniformity, reduce post-harvest losses, enhance food safety, and promote sustainable renewable-energy-based agro-processing technologies for rural communities in The Gambia. The engineering configuration, airflow strategy, and construction specifications are based on the improved prototype developed for research and field testing.

1.2 Problem Statement

Despite favorable climatic conditions for mango production and abundant solar energy resources, The Gambia continues to experience substantial post-harvest losses due to inadequate preservation and processing technologies. During the peak harvesting season (May to July), the volume of fresh mangoes often exceeds local consumption and market demand, resulting in considerable quantities of fruit being wasted before reaching consumers or processing facilities (FAO, 2023; MoALFS, 2022). These losses reduce farmers' incomes, weaken the competitiveness of the mango value chain, and limit opportunities for agro-industrial development and export diversification.

Conventional open-sun drying remains the predominant preservation method in many rural communities because of its low cost and simplicity. However, this traditional practice exposes mango slices to dust, insects, rodents, birds, rainfall, and microbial contamination while providing little control over drying temperature, humidity, or airflow (El-Sebaii & Shalaby, 2012; Bala, 2017). As a result, dried products often exhibit inconsistent quality, discoloration, nutrient degradation, poor hygienic standards, and reduced market value.

Although several indirect solar drying technologies have been developed for tropical environments, many low-cost cabinet dryers continue to experience significant engineering limitations. Poor airflow distribution, inadequate ventilation, insufficient chimney draft, excessive internal humidity, and uneven heat transfer frequently result in prolonged drying

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times and mould formation, particularly under humid environmental conditions (Jain & Tiwari, 2004; Fudholi et al., 2015). These shortcomings reduce drying efficiency, increase product losses, and discourage adoption by smallholder farmers and rural agro-processors.

In The Gambia, limited locally adapted engineering designs further constrain the widespread use of solar drying technologies. Many imported or generalized dryer designs fail to account for the country's climatic characteristics, locally available construction materials, fabrication skills, and the operational needs of rural communities. Consequently, there remains a need for a scientifically designed, affordable, and efficient indirect solar dryer capable of improving airflow distribution, maintaining optimal drying temperatures, enhancing moisture removal, and minimizing microbial growth under Gambian environmental conditions.

This study addresses this gap through the design, development, and engineering evaluation of an improved indirect natural-convection solar mango dryer specifically adapted to the climatic conditions of The Gambia. The proposed system incorporates an optimized solar air collector, insulated drying chamber, balanced inlet and outlet ventilation, food-grade drying trays, and an enhanced chimney-assisted natural convection system to improve drying efficiency, reduce post-harvest losses, and support sustainable mango processing using renewable energy. The engineering design and operating principles are based on the prototype described in the accompanying design package developed for research and field testing in The Gambia.

1.3 Research Aim

The aim of this study is to **design, develop, and evaluate an improved indirect natural-convection solar mango dryer that enhances drying performance, minimizes post-harvest losses, and promotes sustainable mango preservation under the climatic conditions of The Gambia.**

1.4 Research Objectives

1.4.1 General Objective

The general objective of this study is to **design, develop, and evaluate an improved indirect natural-convection solar mango dryer for sustainable post-harvest preservation under the climatic conditions of The Gambia.**

1.4.2 Specific Objectives

To achieve the general objective, the study seeks to:

1. Design an improved indirect solar mango dryer using locally available construction materials suitable for rural communities in The Gambia.

2. Optimize the solar collector, drying chamber, tray arrangement, and chimney-assisted natural ventilation system to improve airflow distribution and thermal efficiency.

3. Evaluate the thermal performance of the dryer by monitoring drying air temperature, relative humidity, airflow, and solar radiation during mango drying operations.

4. Determine the drying characteristics of mango slices, including drying time, moisture removal rate, moisture ratio, and drying efficiency under natural-convection conditions.

5. Assess the effectiveness of the improved dryer in minimizing mould formation, microbial contamination, and quality deterioration compared with traditional open-sun drying methods.

6. Evaluate the economic feasibility and practical applicability of the proposed dryer for smallholder farmers, women's cooperatives, and rural agro-processing enterprises in The Gambia.

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7. Examine the potential contribution of the improved solar dryer to reducing post-harvest losses, enhancing food security, promoting renewable energy utilization, and supporting climate-resilient agricultural development in The Gambia.

1.5 Research Questions

This study is guided by the following research questions:

1. How can an improved indirect solar mango dryer be designed to meet the climatic and socio-economic conditions of The Gambia? .

2. How does the improved airflow management system influence drying temperature, relative humidity, and moisture removal during mango drying?

3. What is the thermal performance of the proposed dryer under natural solar radiation conditions?
4. How effective is the improved dryer in reducing drying time and preventing mould formation compared with traditional open-sun drying?

5. What are the moisture removal characteristics and drying efficiency of the proposed indirect solar dryer?

6. Is the proposed dryer economically feasible and technically suitable for adoption by small-scale mango processors in The Gambia?

7. What potential role can the improved solar dryer play in reducing post-harvest losses and strengthening the mango value chain in The Gambia?

1.6 Research Hypotheses

The study tests the following hypotheses:

Null Hypothesis (H_0)

The improved indirect solar mango dryer does **not** significantly improve drying performance, reduce drying time, enhance product quality, or reduce post-harvest losses compared with conventional open-sun drying methods under the climatic conditions of The Gambia.

Alternative Hypothesis (H_1)

The improved indirect solar mango dryer **significantly improves** drying performance, reduces drying time, enhances product quality, minimizes mould formation, and reduces post-harvest losses compared with conventional open-sun drying methods under the climatic conditions of The Gambia.

1.7 Significance of the Study

This study contributes to the advancement of sustainable agricultural engineering by developing an improved indirect solar mango dryer specifically designed for the environmental and socio-economic conditions of The Gambia. The research integrates renewable energy principles, thermal engineering, and post-harvest technology to address one of the country's major agricultural challenges—high post-harvest losses of mangoes.

From an engineering perspective, the study provides a locally adaptable dryer design that improves airflow distribution, heat transfer, and moisture removal through an optimized solar collector, insulated drying chamber, and chimney-assisted natural-convection system. These improvements are expected to enhance drying efficiency, produce safer and higher-quality dried mango products, and reduce mould development. The design also emphasizes affordability by using locally available materials and fabrication techniques, increasing its potential for widespread adoption. The engineering concepts and prototype configuration are based on the improved indirect solar dryer developed for research and field testing in The Gambia.

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Economically, the proposed dryer has the potential to increase farmers' incomes by reducing fruit spoilage and creating opportunities for value-added mango products. Improved preservation can extend product shelf life, enable market expansion beyond the harvest season, and support the development of small and medium-sized agro-processing enterprises.

Socially, the technology can strengthen food security, create employment opportunities, and empower women and youth who are actively engaged in fruit processing and marketing in rural communities. By reducing food waste and improving product quality, the dryer can contribute to improved nutrition and household livelihoods.

Environmentally, the use of solar energy as the primary heat source reduces dependence on firewood, charcoal, diesel, and grid electricity, thereby lowering greenhouse gas emissions and supporting climate change mitigation efforts. The study aligns with the principles of sustainable development and climate-smart agriculture by promoting clean energy technologies for food processing.

Finally, this research provides valuable scientific and engineering information for policymakers, researchers, development partners, non-governmental organizations, and private investors interested in scaling sustainable post-harvest technologies in The Gambia and across West Africa. The findings are expected to contribute to the achievement of several **United Nations Sustainable Development Goals (SDGs)**, particularly **SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).**

2. Literature Review

2.1 Global Mango Production and Post-Harvest Losses

Mango (*Mangifera indica* L.) is one of the most economically important tropical fruit crops in the world and is cultivated in more than 100 countries across Asia, Africa, Latin America, and Oceania. The fruit is highly valued because of its nutritional composition, pleasant flavor, versatility in food processing, and economic significance in domestic and international markets. Mangoes are rich in carbohydrates, dietary fiber, vitamins A, C, and E, carotenoids, phenolic compounds, and essential minerals, making them an important component of healthy diets and food security (Yahia, 2019; FAO, 2023).

According to the Food and Agriculture Organization (FAO, 2023), global mango production has increased steadily over the past two decades due to expanding cultivation areas, improved crop varieties, and increasing international demand. India remains the world's largest producer, accounting for approximately 40% of global production, followed by countries such as Indonesia, China, Pakistan, Mexico, Nigeria, Brazil, Thailand, Bangladesh, and the Philippines (FAO, 2023). In Africa, mango production has grown significantly because of favorable climatic conditions and increasing investments in horticultural development, with countries such as Nigeria, Kenya, Egypt, Côte d'Ivoire, Mali, Burkina Faso, Senegal, and Ghana becoming major producers (African Development Bank [AfDB], 2022).

Despite increasing production, post-harvest losses remain one of the greatest challenges affecting the global mango industry. Fresh mangoes are highly perishable because of their high moisture content (approximately 80–85%), elevated respiration rate, and susceptibility to microbial spoilage, mechanical damage, and physiological deterioration after harvesting (Kader, 2005; Bechoff et al., 2018). Without appropriate preservation technologies, harvested mangoes rapidly lose quality during harvesting, transportation, storage, and marketing, particularly in tropical and subtropical regions where ambient temperatures accelerate ripening and spoilage.

The FAO estimates that post-harvest losses for fruits and vegetables in developing countries range between **30% and 50%**, depending on crop type, climatic conditions, handling practices, and market infrastructure (FAO, 2023). These losses represent not only wasted food but also substantial economic losses for farmers, traders, processors, and national economies. Furthermore, food losses contribute to unnecessary consumption of land, water, labor, and energy resources while increasing greenhouse gas emissions associated with agricultural production (Gustavsson et al., 2011).

In sub-Saharan Africa, inadequate transportation systems, limited cold-chain infrastructure, insufficient processing facilities, poor packaging, and unreliable electricity supply significantly increase post-harvest losses of mangoes and other

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horticultural products (World Bank, 2024). Smallholder farmers are particularly vulnerable because they often depend on local markets that become saturated during peak harvest periods, forcing producers either to sell fruit at very low prices or allow it to spoil before sale.

In The Gambia, mango production is widespread across the country's agricultural regions, where both indigenous and improved varieties are cultivated by smallholder farmers. Mangoes constitute an important seasonal source of nutrition and household income. However, commercialization remains constrained by inadequate post-harvest management, limited processing technologies, and insufficient market access (MoALFS, 2022). During the peak harvest season, large quantities of fresh mangoes remain unharvested or are discarded because processing capacity is insufficient to absorb the available supply. This situation represents a missed opportunity for value addition, employment creation, export development, and poverty reduction.

Reducing post-harvest losses has therefore become a strategic priority for improving food security, increasing farmers' incomes, and strengthening agricultural value chains throughout developing countries. The FAO emphasizes that investments in improved preservation technologies—including solar drying, cold storage, packaging, and agro-processing—offer practical and cost-effective approaches for reducing food losses while promoting sustainable agricultural development (FAO, 2023). Among these technologies, solar drying is particularly attractive in countries such as The Gambia because of abundant year-round solar radiation, relatively low operating costs, and limited dependence on conventional energy sources.

Consequently, the development of efficient, affordable, and locally adaptable solar drying technologies represents an important opportunity to transform surplus seasonal mango production into high-value dried products with extended shelf life, improved marketability, and increased economic returns for rural households. Such technologies can play a significant role in strengthening food security, reducing waste, promoting renewable energy utilization, and supporting climate-resilient agricultural systems throughout The Gambia and the wider West African region.

2.2 Mango Production and Post-Harvest Challenges in The Gambia

Mango is one of the most widely cultivated fruit crops in The Gambia and plays an important role in household nutrition, income generation, and rural livelihoods. The crop is predominantly grown by smallholder farmers in the **West Coast Region (WCR), North Bank Region (NBR), Lower River Region (LRR), Central River Region (CRR), and Upper River Region (URR)**, where favorable climatic conditions support both indigenous and improved mango varieties (MoALFS, 2022). In addition to household consumption, mango production provides seasonal employment opportunities in harvesting, transportation, processing, and local marketing. The increasing demand for fresh and processed mango products presents significant opportunities for expanding agro-processing industries and improving export competitiveness.

The Gambia experiences a tropical Sudan-Sahelian climate characterized by a long dry season (November to May) and a short rainy season (June to October). Annual temperatures generally range from **24°C to 38°C**, while average daily solar radiation exceeds **5.5 kWh m^{-2} day^{-1}** throughout much of the year, providing favorable conditions for solar-based agricultural technologies (World Bank, 2024; National Environment Agency [NEA], 2021). These climatic conditions make solar drying an attractive and environmentally sustainable alternative to conventional drying methods, particularly in rural communities where access to electricity is limited.

Despite favorable growing conditions, mango production in The Gambia is characterized by significant seasonal fluctuations. During the peak harvesting period, which typically occurs between **May and July**, fruit production exceeds local market demand. Because fresh mangoes have a limited storage life and cold-chain infrastructure remains underdeveloped, substantial quantities of fruit deteriorate before they can be consumed, transported, or processed (FAO, 2023; MoALFS, 2022). These post-harvest losses reduce farm profitability and discourage further investment in commercial mango production.

Several factors contribute to these losses. First, many rural communities lack adequate storage facilities capable of maintaining fruit quality after harvest. Second, transportation networks connecting production areas to urban markets are

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often inadequate, increasing the likelihood of mechanical damage and spoilage during transit. Third, limited access to processing technologies prevents producers from converting surplus fresh mangoes into value-added products such as dried mango slices, juices, concentrates, jams, and powders. Consequently, farmers frequently sell fresh fruit at low prices during the harvest season or allow unsold produce to spoil in orchards.

Traditional preservation methods, particularly open-sun drying, remain widely practiced because they require minimal financial investment. However, open-sun drying presents numerous disadvantages, including prolonged drying periods, exposure to dust, insects, birds, rodents, rainfall, and microbial contamination (El-Sebaii & Shalaby, 2012). Furthermore, uncontrolled environmental conditions often result in uneven drying, discoloration, nutrient degradation, and poor product quality, reducing consumer acceptance and market value. These limitations restrict the commercial potential of dried mango products produced using traditional techniques.

Although solar dryers have been introduced in several developing countries as an alternative preservation technology, many existing designs are not well suited to Gambian conditions. Common engineering challenges include inadequate airflow distribution, insufficient insulation, poor moisture removal, excessive heat losses, and limited capacity to maintain consistent drying temperatures under varying weather conditions (Fudholi et al., 2015; Bala, 2017). In addition, many imported dryer designs rely on construction materials or fabrication techniques that are expensive or difficult to obtain locally, limiting their adoption by rural communities.

Another important challenge is the occurrence of mould during drying. High ambient humidity, inadequate ventilation, excessive tray loading, and poor air circulation frequently prevent sufficient moisture removal from mango slices. Under these conditions, warm and humid air becomes trapped inside the drying chamber, creating an environment favorable for fungal growth and product spoilage. These problems have been identified as major constraints to the successful operation of naturally ventilated cabinet dryers and emphasize the importance of optimizing airflow, ventilation, and chimney design in solar drying systems. The improved indirect solar dryer proposed in this study addresses these engineering limitations by incorporating a balanced inlet–outlet airflow system, an insulated drying chamber, optimized tray spacing, and a chimney-assisted natural convection mechanism to enhance moisture removal and improve drying uniformity. These design improvements are described in detail in the prototype engineering package developed for field application in The Gambia.

Beyond reducing food losses, improving mango preservation technologies has broader implications for national development. Efficient solar drying systems can increase farmers' incomes through value addition, extend product shelf life, improve food availability beyond the harvest season, create employment opportunities in rural agro-processing enterprises, and promote entrepreneurship among women and youth. Moreover, replacing fuel-based drying methods with renewable solar energy contributes to reducing greenhouse gas emissions and supports The Gambia's commitments to sustainable development and climate change mitigation.

Given these challenges and opportunities, there is a clear need for a scientifically designed, affordable, and locally adaptable solar drying system capable of improving product quality while reducing post-harvest losses. Developing such technology represents an important step toward strengthening the mango value chain, enhancing food security, and promoting sustainable agro-industrial development in The Gambia.

2.3 Principles of Solar Drying Technology

Solar drying is one of the oldest and most environmentally sustainable methods of preserving agricultural products by reducing their moisture content to levels that inhibit microbial growth, enzymatic activity, and biochemical deterioration. Unlike traditional open-sun drying, which exposes food directly to environmental contaminants, modern solar drying systems utilize enclosed drying chambers that provide controlled drying conditions, resulting in improved product quality, enhanced food safety, and reduced post-harvest losses (Esper & Mühlbauer, 1998; Bala, 2017).

The fundamental objective of solar drying is to remove moisture from agricultural products by transferring thermal energy from solar radiation to the drying air. Heated air absorbs moisture from the product surface and carries it away through continuous airflow, thereby lowering the moisture content to safe storage levels (Mujumdar, 2015). The drying process is

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governed by simultaneous heat and mass transfer mechanisms in which heat energy is supplied to evaporate moisture while mass transfer removes the resulting water vapor from the drying chamber (Brooker et al., 1992).

Solar energy is particularly suitable for agricultural drying because it is abundant, renewable, environmentally friendly, and freely available in many tropical and subtropical countries. The Gambia receives high levels of solar irradiance throughout the year, averaging approximately **5.5–6.5 kWh m^{-2} day^{-1}**, making solar drying a technically feasible and economically attractive preservation technology for rural communities (World Bank, 2024; International Renewable Energy Agency [IRENA], 2023). The widespread availability of solar energy provides opportunities for reducing dependence on conventional fuels while supporting sustainable food processing and climate-resilient agriculture.

The efficiency of any solar drying system depends primarily on its ability to collect solar energy, transfer heat effectively to the drying air, and continuously remove moisture from the drying chamber. Consequently, the design of the solar collector, airflow pathway, insulation, tray arrangement, and ventilation system plays a critical role in determining overall drying performance. Poor airflow distribution or inadequate ventilation can result in excessive humidity accumulation inside the drying chamber, slowing the drying process and increasing the likelihood of microbial growth and mould development (Jain & Tiwari, 2004; Fudholi et al., 2015).

During the drying process, moisture removal generally occurs in two distinct phases. The first is the **constant-rate drying period**, during which free surface moisture evaporates rapidly because sufficient moisture is readily available at the product surface. This phase is largely controlled by external conditions such as drying air temperature, airflow velocity, and relative humidity. As drying progresses, the product enters the **falling-rate drying period**, during which moisture must diffuse from the interior of the material to its surface before evaporation can occur. This second stage is primarily governed by the physical properties of the product, including moisture diffusivity, slice thickness, cellular structure, and internal resistance to moisture movement (Mujumdar, 2015; Yahia, 2019).

For mango slices, the falling-rate period accounts for the majority of the drying process because the fruit contains a large quantity of bound moisture within its cellular structure. Consequently, maintaining a stable drying temperature and continuous airflow throughout the drying chamber is essential for achieving uniform moisture removal and preventing localized moisture accumulation. Excessive drying temperatures may cause case hardening, discoloration, shrinkage, nutrient degradation, and loss of desirable sensory characteristics, whereas insufficient temperatures or inadequate airflow can significantly prolong drying time and increase the risk of fungal growth (Bechoff et al., 2018).

The design developed in this study applies the principles of indirect solar drying, in which solar radiation heats air inside a separate solar collector before the heated air enters the drying chamber. Unlike direct solar dryers, the product is not exposed to direct sunlight, thereby reducing ultraviolet degradation, discoloration, and nutrient losses while maintaining better product appearance and nutritional quality (El-Sebaii & Shalaby, 2012). The heated air flows through stacked food-grade drying trays, absorbs moisture from the mango slices, and exits through a vertical chimney that enhances natural convection by creating a pressure difference between the inlet and outlet openings. This continuous airflow mechanism promotes efficient moisture removal while minimizing internal humidity. The engineering configuration—including the insulated drying chamber, optimized collector dimensions, balanced inlet and outlet openings, controlled tray spacing, and chimney-assisted ventilation—is specifically intended to maximize natural airflow under the climatic conditions of The Gambia. These design principles are incorporated into the improved prototype presented in the engineering design package.

Understanding these scientific principles provides the theoretical foundation for designing high-performance solar dryers capable of producing safe, hygienic, and high-quality dried mango products. An optimized drying system should therefore maximize solar energy utilization, maintain stable drying conditions, promote uniform airflow, and continuously remove moisture while preserving the nutritional and sensory qualities of the dried product. These principles form the basis for the engineering design and performance evaluation presented in this study.

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2.4 Classification of Solar Drying Systems

Solar dryers can be classified according to the method of solar energy utilization, airflow generation, and heat transfer mechanism. The most common classifications include **direct solar dryers, indirect solar dryers, mixed-mode solar dryers, and hybrid solar dryers**. Each technology has unique operational characteristics, advantages, and limitations depending on climatic conditions, product type, drying capacity, and intended application (Bala, 2017; Mujumdar, 2015). Understanding these systems is essential for selecting the most appropriate technology for mango preservation under the environmental conditions of The Gambia.

2.4.1 Direct Solar Dryers

Direct solar dryers expose agricultural products directly to incoming solar radiation within an enclosed transparent chamber. Solar energy passes through a transparent cover made of glass or plastic and is absorbed by the product and internal surfaces, converting radiant energy into heat. The heated air inside the chamber removes moisture from the product while natural or forced ventilation allows humid air to escape (Esper & Mühlbauer, 1998).

Direct solar dryers are relatively simple to construct and require minimal materials, making them attractive for small-scale rural applications. Their low construction cost and straightforward operation have led to widespread adoption in many developing countries. However, continuous exposure to direct sunlight can negatively affect product quality by causing discoloration, degradation of vitamins, loss of aroma compounds, and reduced sensory characteristics. In addition, direct solar dryers often experience uneven temperature distribution because the product itself absorbs a substantial portion of the incoming solar radiation (El-Sebaii & Shalaby, 2012).

For heat-sensitive products such as mango slices, prolonged exposure to ultraviolet radiation may reduce nutritional quality and consumer acceptance. Consequently, direct solar dryers are generally less suitable for producing premium-quality dried fruit intended for commercial markets.

2.4.2 Indirect Solar Dryers

Indirect solar dryers separate the solar collector from the drying chamber. In this configuration, solar radiation heats air inside a dedicated solar collector rather than directly heating the product. The heated air is then directed into the drying chamber, where it transfers heat to the product and removes moisture before exiting through a ventilation system (Bala, 2017).

This arrangement offers several important advantages. Since the product is protected from direct sunlight, deterioration caused by ultraviolet radiation is minimized, resulting in improved color retention, nutritional quality, and overall product appearance. Furthermore, separating the collector from the drying chamber allows better control of airflow and temperature distribution, leading to more uniform drying conditions (Fudholi et al., 2015).

Indirect solar dryers generally produce higher-quality dried products than direct systems and are widely recommended for fruits, vegetables, medicinal plants, herbs, and other high-value agricultural commodities. Their principal disadvantages include higher construction costs and greater engineering complexity due to the additional solar collector, ducting system, and airflow management components.

The improved mango dryer proposed in this study adopts the indirect drying principle because it offers superior product quality, better hygiene, and improved thermal control under Gambian climatic conditions. The design incorporates a separate solar air collector, insulated drying chamber, optimized tray spacing, and chimney-assisted natural convection to maximize drying efficiency. These engineering features are described in the prototype design package.

2.4.3 Mixed-Mode Solar Dryers

Mixed-mode solar dryers combine the operating principles of both direct and indirect drying systems. In these dryers, agricultural products receive heat simultaneously from direct solar radiation entering through transparent chamber surfaces and from heated air supplied by a solar collector (Mujumdar, 2015).

Mixed-mode systems generally achieve higher drying temperatures and shorter drying times than either direct or indirect dryers alone. However, direct exposure of the product to sunlight may still result in nutrient degradation and discoloration, particularly for light-sensitive products such as mangoes. In addition, mixed-mode systems often require more sophisticated structural designs to balance solar radiation, airflow, and temperature distribution effectively.

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Although mixed-mode dryers provide high thermal performance, they may not always be appropriate for rural communities seeking simple, affordable, and easily maintainable technologies.

2.4.4 Hybrid Solar Dryers

Hybrid solar dryers combine solar energy with supplementary heat sources such as electricity, biomass, liquefied petroleum gas (LPG), biogas, or photovoltaic-powered electrical heaters. These systems are designed to maintain drying operations during cloudy weather, nighttime, or periods of reduced solar radiation (Fudholi et al., 2015).

Hybrid systems provide continuous drying capability and greater operational flexibility than purely solar-powered dryers. They are particularly useful for commercial-scale processing facilities that require uninterrupted production regardless of weather conditions. However, the additional heating equipment increases construction costs, operating expenses, maintenance requirements, and dependence on external energy sources.

For rural communities in The Gambia, where affordability and energy independence are important considerations, hybrid systems may not be economically feasible for small-scale processors. Nevertheless, photovoltaic-assisted ventilation fans could provide a practical enhancement to natural-convection dryers during periods of high humidity.

2.4.5 Natural-Convection and Forced-Convection Solar Dryers

Solar dryers are also classified according to the method used to move drying air through the system.

Natural-Convection Solar Dryers

Natural-convection dryers rely on buoyancy forces generated by differences in air temperature and density. As solar-heated air becomes less dense, it rises naturally through the drying chamber and exits through a chimney or exhaust opening. Cooler ambient air enters through lower inlet openings, creating continuous airflow without mechanical assistance (Brooker et al., 1992).

Natural-convection dryers have several advantages:

- No electricity requirement.
- Low operating and maintenance costs.
- Simple construction.
- Suitable for remote rural communities.
- Environmentally sustainable.

However, airflow depends on weather conditions, chimney height, temperature differences, and system design. Consequently, poorly designed natural-convection dryers may experience insufficient ventilation under humid conditions.

Forced-Convection Solar Dryers

Forced-convection dryers utilize electrically powered fans to move heated air through the drying chamber. The increased airflow generally results in shorter drying times, improved temperature uniformity, and higher drying capacity than natural-convection systems (Bala, 2017).

Despite these advantages, forced-convection systems require reliable electricity or photovoltaic power, increasing both installation and operating costs. Fan maintenance and electrical system reliability may also present challenges in rural areas.

2.4.6 Justification for Selecting an Indirect Natural-Convection Solar Dryer

The improved dryer developed in this research employs an **indirect natural-convection configuration** because it represents the most appropriate balance between engineering performance, affordability, sustainability, and practicality for rural communities in The Gambia. The country's abundant solar radiation, combined with limited access to grid electricity in many agricultural areas, makes passive solar drying an attractive preservation technology.

Unlike traditional cabinet dryers, the proposed design incorporates an optimized solar collector, insulated drying chamber, balanced inlet and outlet openings, food-grade drying trays, and an extended chimney with an adjustable damper to strengthen natural airflow and improve moisture removal. These engineering modifications are intended to reduce drying time, improve temperature uniformity, minimize mould formation, and produce higher-quality dried mango products while

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maintaining low construction and operating costs. The configuration is based on the prototype developed for research and field evaluation under Gambian climatic conditions.

Overall, the indirect natural-convection solar dryer provides a practical and technically appropriate solution for reducing post-harvest losses, improving food preservation, and promoting renewable-energy-based agro-processing in The Gambia.

2.5 Heat and Mass Transfer Mechanisms in Solar Drying

The performance of a solar drying system is fundamentally governed by the simultaneous processes of **heat transfer** and **mass transfer**. During drying, thermal energy supplied by solar radiation is transferred to the drying air, which subsequently transfers heat to the agricultural product. This heat provides the latent energy required to evaporate moisture from the product surface. At the same time, moisture migrates from the interior of the product to its surface through diffusion before being removed by the moving air stream. The interaction between these two processes determines the drying rate, product quality, energy efficiency, and overall performance of the solar dryer (Mujumdar, 2015; Brooker et al., 1992).

Figure 5 illustrates the natural-convection airflow pattern within the improved indirect solar mango dryer. Ambient air enters the solar collector through the lower inlet openings, where it is heated before entering the drying chamber. The heated air rises naturally through the stacked drying trays, transferring thermal energy to the mango slices while simultaneously absorbing moisture. As the air becomes warmer and moisture-laden, it continues upward and exits through the chimney, creating a continuous buoyancy-driven airflow that enhances drying efficiency and promotes uniform moisture removal throughout the chamber.

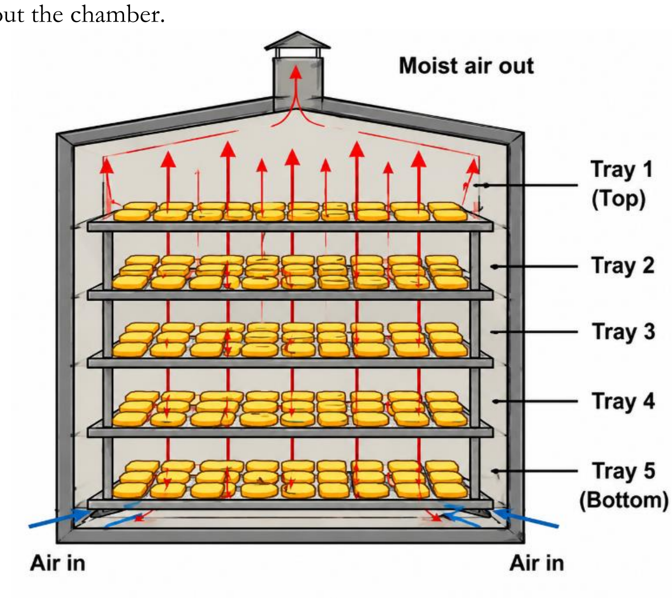

Fig. 1. Airflow distribution inside the improved indirect solar mango dryer illustrating the natural-convection airflow path. Heated air enters through the lower inlets, circulates uniformly across the drying trays, absorbs moisture from the mango slices, and exits through the chimney as warm, moisture-laden air.

2.5.1 Heat Transfer Mechanisms

Heat transfer within a solar dryer occurs through three primary mechanisms: **solar radiation**, **conduction**, and **convection**.

Solar Radiation

Solar radiation is the principal source of thermal energy in solar drying systems. Incoming short-wave solar radiation passes through the transparent glazing of the solar collector and is absorbed by the blackened absorber plate, where it is converted

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into thermal energy. The heated absorber subsequently transfers heat to the air flowing through the collector before the heated air enters the drying chamber (Duffie & Beckman, 2013).

The amount of useful thermal energy generated depends on several factors, including solar irradiance, collector orientation, collector tilt angle, absorber surface properties, glazing material, and ambient weather conditions. Because The Gambia lies between approximately **13° and 14° North latitude**, the available solar resource is highly favorable for solar thermal applications throughout most of the year (IRENA, 2023).

The useful heat gain from the solar collector can be expressed as:

$$Q_u = \dot{m}C_p(T_o - T_i)$$

where:

- Q_u= Useful heat gain (W)
- $\dot{m}$= Mass flow rate of air (kg s^{-1})
- C_p= Specific heat capacity of air (J kg^{-1} K^{-1})
- T_o= Collector outlet temperature (°C)
- T_i= Collector inlet temperature (°C)

This equation forms the basis for evaluating collector thermal performance during experimental testing.

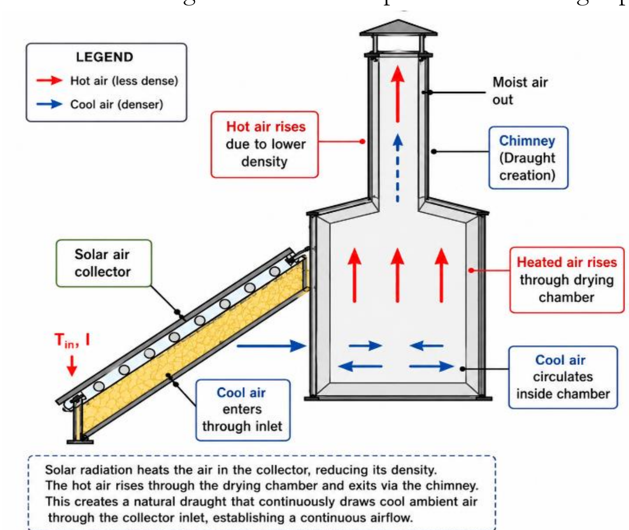

Fig. 2. *Chimney-assisted natural convection mechanism in the improved indirect solar mango dryer. Solar-heated air rises through the drying chamber because of density differences, creating a buoyancy-driven airflow that continuously removes moisture-laden air through the chimney while drawing fresh ambient air through the solar collector.*

Conduction

Conduction refers to heat transfer through solid materials such as the absorber plate, cabinet walls, insulation, tray supports, and structural components. Efficient conduction within the absorber plate improves heat transfer to the circulating air, whereas excessive conduction through poorly insulated chamber walls results in undesirable heat losses to the surrounding environment (Incropera et al., 2017).

To minimize conductive heat loss, the proposed dryer incorporates insulated chamber walls and collector insulation beneath the absorber plate. These design features improve thermal efficiency by retaining heat within the drying system and maintaining relatively stable drying temperatures throughout the drying period. The insulation strategy is incorporated into the engineering design described in the prototype package.

Convection

Convection is the dominant heat transfer mechanism within the drying chamber. Heated air leaving the solar collector flows through the stacked trays containing mango slices, transferring thermal energy to the fruit surface. As moisture evaporates, humid air becomes lighter and rises naturally toward the chimney outlet, while cooler ambient air enters through the lower inlet openings, maintaining continuous airflow.

Natural convection within the dryer is governed primarily by:

- Temperature difference between inlet and outlet air
- Air density variation
- Chimney height
- Airflow resistance
- Inlet and outlet opening sizes
- Atmospheric conditions

An efficient natural-convection system promotes uniform temperature distribution while continuously removing moisture-laden air from the drying chamber.

The three fundamental modes of heat transfer involved in the operation of the improved indirect solar mango dryer are illustrated in Fig. 7. Solar radiation provides the primary energy input to the collector, where the absorber plate converts incident solar energy into thermal energy. Heat is subsequently conducted through the absorber plate and transferred to the flowing air, while convection transports the heated air through the drying chamber to remove moisture from the mango slices. These combined mechanisms are responsible for the thermal performance and drying efficiency of the system.

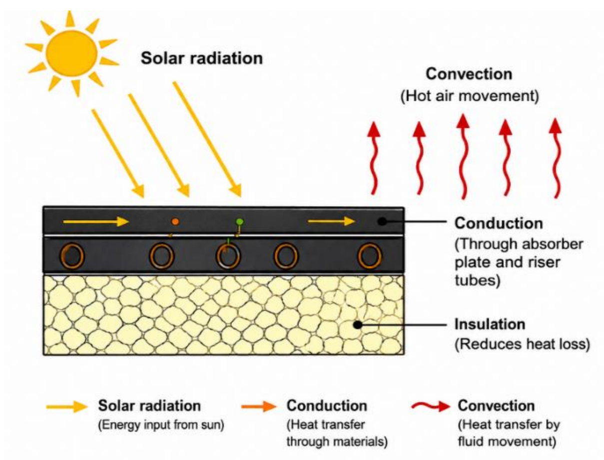

Fig. 3. *Heat transfer mechanisms in the flat-plate solar air collector illustrating the interaction of solar radiation, conduction through the absorber plate, and convection to the drying air. Thermal insulation beneath the absorber minimizes conductive heat losses and improves collector efficiency.*

2.5.2 Mass Transfer Mechanisms

Mass transfer refers to the movement of moisture from the interior of the mango slices to the surrounding drying air. Initially, free moisture located near the product surface evaporates rapidly. As drying progresses, moisture located deeper within the fruit tissue migrates toward the surface by diffusion before evaporation can continue (Mujumdar, 2015).

The driving force for moisture movement is the moisture concentration gradient between the interior of the product and the surrounding drying air. Increasing drying air temperature while reducing relative humidity increases this gradient, thereby accelerating moisture removal.

Several factors influence moisture migration, including:

- Air temperature
- Relative humidity

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- Air velocity
- Slice thickness
- Initial moisture content
- Product composition
- Drying duration

For mango slices, moisture removal occurs predominantly during the falling-rate period because internal diffusion becomes the controlling mechanism after surface moisture has evaporated.
During solar drying, moisture migrates from the interior of mango slices toward the surface because of the combined effects of temperature gradients, vapor pressure differences, and internal diffusion. Initially, the fruit contains a high moisture content distributed throughout its cellular structure. As heat is transferred to the product, moisture moves toward the surface where it evaporates into the surrounding drying air. Figure 7 illustrates this moisture migration process, highlighting the reduction in moisture content and the progressive shrinkage of the mango slices during drying.

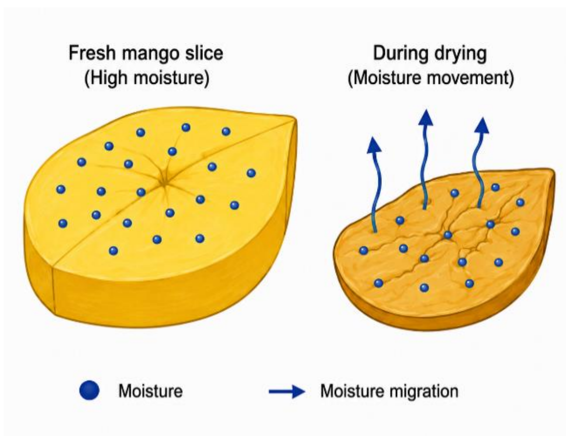

Fig. 4. *Illustration of moisture migration within mango slices during indirect solar drying. Moisture diffuses from the interior of the fresh fruit toward the surface, where it evaporates into the surrounding heated air, resulting in progressive dehydration and product shrinkage.*

2.5.3 Drying Kinetics

Drying kinetics describe the rate at which moisture is removed from the product during drying. Two principal drying stages are generally observed.

Constant-Rate Period

The constant-rate period occurs immediately after loading when free water is readily available on the product surface. During this stage, evaporation proceeds rapidly and is primarily controlled by external drying conditions, including air temperature, airflow velocity, and relative humidity (Brooker et al., 1992).

Falling-Rate Period

Once surface moisture has been depleted, the drying process enters the falling-rate period. Moisture must then migrate from the interior of the mango tissue to the surface before evaporation can occur. Consequently, the drying rate gradually decreases as moisture content declines.

For mango slices, the falling-rate period represents the largest proportion of the drying process and largely determines the total drying time (Yahia, 2019).

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2.5.4 Moisture Ratio

Drying performance is commonly evaluated using the moisture ratio (MR), expressed as:

$$MR = \frac{M_t - M_e}{M_o - M_e}$$

where:

- M_t = Moisture content at time t
- M_o = Initial moisture content
- M_e = Equilibrium moisture content

Because the equilibrium moisture content is usually very small compared with the initial moisture content, the equation is often simplified to:

$$MR = \frac{M_t}{M_o}$$

The moisture ratio provides a dimensionless measure of drying progress and is widely used for comparing drying performance under different operating conditions.

2.5.5 Drying Rate

The drying rate indicates the amount of moisture removed from the product over time and can be calculated as:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t}$$

where:

- DR = Drying rate (kg water h^{-1})
- M_t = Moisture content at time t
- $M_{t+\Delta t}$ = Moisture content at the next observation
- Δt = Time interval

Drying rate curves provide valuable information regarding dryer performance and are commonly used to compare different drying technologies.

2.5.6 Importance of Heat and Mass Transfer in Dryer Design

Efficient heat and mass transfer are essential for achieving rapid moisture removal while preserving the nutritional and sensory quality of dried mangoes. Inadequate airflow or poor ventilation can lead to moisture accumulation inside the drying chamber, increasing the likelihood of fungal growth and uneven drying. Conversely, excessive temperatures may cause case hardening, shrinkage, discoloration, and degradation of heat-sensitive nutrients.

The improved indirect solar dryer developed in this study addresses these challenges through an optimized combination of a high-efficiency solar collector, insulated drying chamber, balanced airflow pathways, controlled tray spacing, and an enhanced chimney-assisted natural-convection system. Together, these design features improve thermal performance, strengthen natural draft, promote uniform heat distribution, and facilitate continuous removal of moisture-laden air. These engineering principles form the theoretical basis for the performance evaluation presented in later sections of this study and are reflected in the prototype design developed for field testing in The Gambia.

2.6 Previous Studies on Solar Mango Drying

Solar drying has received considerable attention over the past three decades as a sustainable technology for preserving fruits and vegetables while reducing post-harvest losses and improving food security. Numerous studies have investigated the design, thermal performance, drying kinetics, energy efficiency, and product quality associated with different solar

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drying systems. These studies consistently demonstrate that appropriately designed solar dryers can significantly reduce drying time, improve product quality, and increase the shelf life of dried agricultural products compared with traditional open-sun drying (Bala, 2017; Fudholi et al., 2015).

One of the earliest comprehensive investigations into solar drying technology was conducted by **Esper and Mühlbauer (1998)**, who evaluated various natural-convection solar dryers for tropical agricultural products. Their research demonstrated that enclosed solar drying systems substantially reduced contamination from insects, dust, and rainfall while improving drying efficiency. However, they also reported that insufficient ventilation frequently resulted in moisture accumulation within the drying chamber, emphasizing the importance of proper airflow management and ventilation design.

Jain and Tiwari (2004) developed a mathematical model to predict the thermal performance of a cabinet solar dryer operating under natural-convection conditions. Their findings indicated that collector efficiency, airflow velocity, insulation quality, and ambient weather conditions significantly influenced drying performance. They further concluded that chimney height and collector orientation directly affected airflow generation and drying efficiency, suggesting that proper engineering optimization is essential for improving natural-convection dryers.

In Bangladesh, **Bala (2017)** investigated indirect solar drying systems for fruits and vegetables and reported that indirect dryers consistently produced higher-quality dried products than traditional open-sun drying methods. The study found improvements in color retention, nutritional quality, hygiene, and drying uniformity while reducing drying times and microbial contamination. Bala emphasized that indirect solar dryers are particularly suitable for high-value horticultural products because they protect the product from direct solar radiation and environmental contamination.

Similarly, **Fudholi et al. (2015)** reviewed numerous solar drying technologies and concluded that indirect solar dryers generally achieve higher thermal efficiencies than direct solar dryers because they provide better control of heat transfer and airflow. Their review identified collector design, airflow distribution, insulation, and drying chamber configuration as the most influential engineering parameters affecting dryer performance. The authors also highlighted the growing importance of computational modeling and experimental validation in optimizing solar dryer designs.

Several studies have specifically examined mango drying. **Bechoff et al. (2018)** investigated the effects of drying conditions on the nutritional quality of dried mangoes and reported that drying temperature, air velocity, and drying duration significantly influence vitamin retention, color stability, and sensory quality. Their results demonstrated that maintaining moderate drying temperatures while ensuring continuous airflow produces higher-quality dried mango products than exposing fruit to excessive temperatures or prolonged drying periods.

Research conducted in **India**, **Thailand**, and **Malaysia** has consistently shown that indirect solar drying systems reduce drying time by **30–60%** compared with traditional open-sun drying while improving product quality and reducing microbial contamination (El-Sebaii & Shalaby, 2012; Fudholi et al., 2015). These studies emphasize the importance of maintaining stable drying temperatures between **50°C and 65°C**, which provide efficient moisture removal without causing excessive shrinkage, discoloration, or nutrient degradation.

In Africa, solar drying technologies have been investigated for preserving mangoes, bananas, tomatoes, peppers, fish, cassava, and medicinal plants. Studies in **Kenya**, **Ghana**, **Nigeria**, and **Tanzania** have demonstrated that solar dryers improve food quality, reduce post-harvest losses, and create opportunities for value addition among smallholder farmers (AfDB, 2022; FAO, 2023). Nevertheless, widespread adoption remains limited because many existing dryer designs are expensive, difficult to construct locally, or insufficiently adapted to local climatic conditions.

Research undertaken in **West Africa** has further shown that high ambient humidity during certain periods of the year can significantly reduce drying efficiency in naturally ventilated cabinet dryers. Under these conditions, inadequate ventilation often results in condensation within the drying chamber and subsequent mould formation. Several authors have therefore recommended improving airflow distribution through optimized collector geometry, larger inlet openings, improved tray spacing, and taller chimney systems to strengthen natural convection (Jain & Tiwari, 2004; Fudholi et al., 2015).

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Despite the substantial body of international research on solar drying, relatively few peer-reviewed engineering studies have focused specifically on **The Gambia**. Most available information relates to general agricultural development or small-scale demonstration projects rather than comprehensive engineering evaluations of locally adapted solar dryer designs. Consequently, there remains limited scientific evidence regarding the thermal performance, airflow characteristics, drying efficiency, and operational suitability of indirect natural-convection solar dryers under Gambian climatic conditions.
Furthermore, many published studies emphasize laboratory-scale experimental systems or electrically assisted dryers that may not be economically feasible for rural communities with limited access to reliable electricity. There is therefore a need for an affordable, passive solar drying system that can be fabricated using locally available materials while maintaining high drying efficiency and product quality.

The improved indirect solar mango dryer developed in the present study addresses these research gaps by integrating several engineering innovations into a single locally adaptable design. These innovations include a high-efficiency solar air collector, an insulated drying chamber, balanced inlet and outlet ventilation, optimized tray spacing, and an enhanced chimney-assisted natural-convection system designed to improve airflow, reduce internal humidity, and minimize mould formation. Unlike many previous studies, the proposed system has been specifically designed for fabrication using materials readily available in The Gambia and for operation under local climatic conditions. The engineering design also incorporates provisions for temperature and humidity monitoring, enabling future experimental validation and performance optimization. These design characteristics distinguish the present study from previously published work and provide a practical foundation for sustainable mango processing in The Gambia. The engineering concepts and configuration are based on the prototype documented in the accompanying design package.

2.7 Research Gap
Although previous studies have demonstrated the effectiveness of solar drying technologies for preserving mangoes and other horticultural products, several important research gaps remain.

First, **there is a lack of engineering studies specifically designed for the climatic conditions of The Gambia**. Most published solar dryer designs have been developed and evaluated in Asia or other African countries with different environmental conditions, agricultural practices, and construction materials.

Second, **limited attention has been given to optimizing natural-convection airflow** in low-cost cabinet dryers. Poor airflow distribution remains one of the primary causes of uneven drying, excessive humidity, and mould formation in many existing systems.

Third, **few studies integrate thermal design, airflow optimization, material selection, and economic feasibility into a single engineering framework** suitable for rural fabrication and community-scale adoption.
Finally, **experimental data on the performance of locally fabricated indirect solar dryers in The Gambia are scarce**, limiting the ability of policymakers, engineers, and development organizations to promote evidence-based adoption of renewable-energy food preservation technologies.

This study seeks to address these gaps through the design, development, and future performance evaluation of an improved indirect natural-convection solar mango dryer specifically engineered for Gambian environmental conditions. By combining optimized airflow management, thermal engineering, locally available construction materials, and practical fabrication techniques, the proposed system aims to provide a technically robust, economically affordable, and environmentally sustainable solution for reducing mango post-harvest losses and strengthening rural agro-processing in The Gambia.

3. Materials and Methods
3.1 Study Area
This study was conducted in **The Gambia**, the smallest country on the West African mainland, situated between latitudes **13°02' N and 13°50' N** and longitudes **13°47' W and 16°50' W**. The country extends approximately 480 km along the Gambia River and is almost entirely surrounded by Senegal, with a narrow Atlantic coastline to the west. The total land

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area is approximately **11,300 km²**, and the country's geography consists primarily of low-lying plains with elevations generally below 60 m above sea level (NEA, 2021; World Bank, 2024).

Agriculture constitutes one of the principal economic sectors in The Gambia, employing a substantial proportion of the rural population. Horticultural production, particularly fruit cultivation, contributes significantly to household nutrition and income generation. Mango (*Mangifera indica* L.) is among the country's most widely cultivated fruit crops and is grown extensively across the **West Coast Region (WCR), North Bank Region (NBR), Lower River Region (LRR), Central River Region (CRR), and Upper River Region (URR)**. Production is dominated by smallholder farmers who cultivate both indigenous and improved mango varieties for domestic consumption and local markets (MoALFS, 2022).

The climate of The Gambia is classified as **tropical Sudan-Sahelian**, characterized by a distinct dry season extending from **November to May** and a rainy season occurring between **June and October**. Mean annual temperatures typically range from **24°C to 38°C**, while relative humidity varies considerably between seasons, reaching higher values during the rainy months. Annual rainfall generally ranges between **700 mm and 1,200 mm**, increasing from the eastern regions toward the western coastal areas (NEA, 2021).

One of the country's greatest natural resources is its abundant solar energy. Average daily global solar radiation ranges from approximately **5.5 to 6.5 kWh m⁻² day⁻¹**, with more than **3,000 sunshine hours annually**, providing highly favorable conditions for solar thermal applications throughout most of the year (IRENA, 2023; World Bank, 2024). These climatic characteristics make The Gambia particularly suitable for solar drying technologies that utilize natural convection for agricultural processing.

Despite these favorable environmental conditions, significant post-harvest losses continue to occur during the peak mango harvesting season. Fresh mangoes have high moisture content and a short storage life, while access to refrigerated storage and modern processing facilities remains limited in many rural communities. Consequently, a substantial proportion of harvested fruit deteriorates before reaching consumers or processors, highlighting the need for affordable preservation technologies adapted to local environmental conditions (FAO, 2023).

The improved indirect solar mango dryer investigated in this study was specifically designed to operate under the climatic conditions of The Gambia. The engineering design incorporates collector orientation, collector inclination, airflow pathways, and natural-convection principles appropriate for the country's latitude and solar resource. The solar collector is oriented toward **true south** with an inclination angle of **15–20°**, which closely corresponds to the geographical latitude of The Gambia and maximizes annual solar energy capture. These design parameters are intended to provide efficient thermal performance while maintaining simple construction techniques suitable for local fabrication using readily available materials. The prototype dimensions, collector geometry, airflow configuration, and construction details are based on the engineering design package developed for field application in The Gambia.

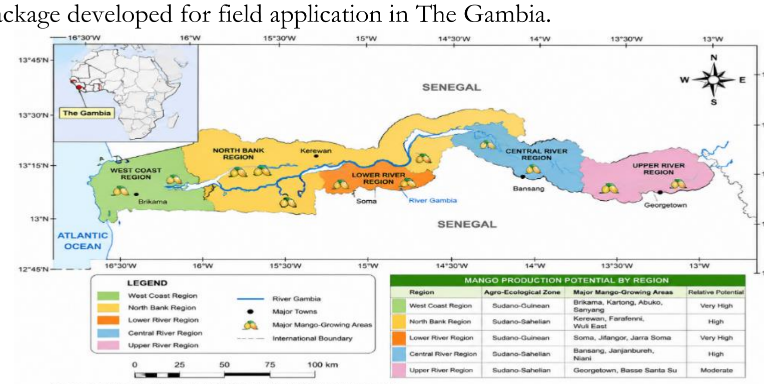

Figure 5: illustrates the study area and the principal mango-growing regions of The Gambia used as the geographical context for this research.

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3.2 Research Design

This study employed an **engineering design and experimental evaluation approach** to develop and assess the performance of an improved indirect natural-convection solar mango dryer. The research combined engineering design principles, thermal analysis, and future experimental validation to evaluate the suitability of the proposed dryer for preserving fresh mangoes under Gambian climatic conditions.

The research consisted of four sequential phases:

1. **Engineering Design Phase:** Development of the solar dryer, including the solar collector, drying chamber, airflow system, chimney, drying trays, and monitoring system.
2. **Construction Phase:** Fabrication of the prototype using locally available construction materials commonly accessible in The Gambia.
3. **Experimental Evaluation Phase:** Performance testing under natural solar conditions to measure drying temperature, relative humidity, airflow, drying rate, moisture reduction, and drying efficiency.
4. **Performance Assessment Phase:** Analysis of thermal performance, product quality, drying kinetics, and economic feasibility to determine the effectiveness of the improved dryer.

The experimental design enables comprehensive evaluation of the dryer under realistic environmental conditions and provides quantitative data for comparison with conventional open-sun drying methods and previously published solar drying studies.

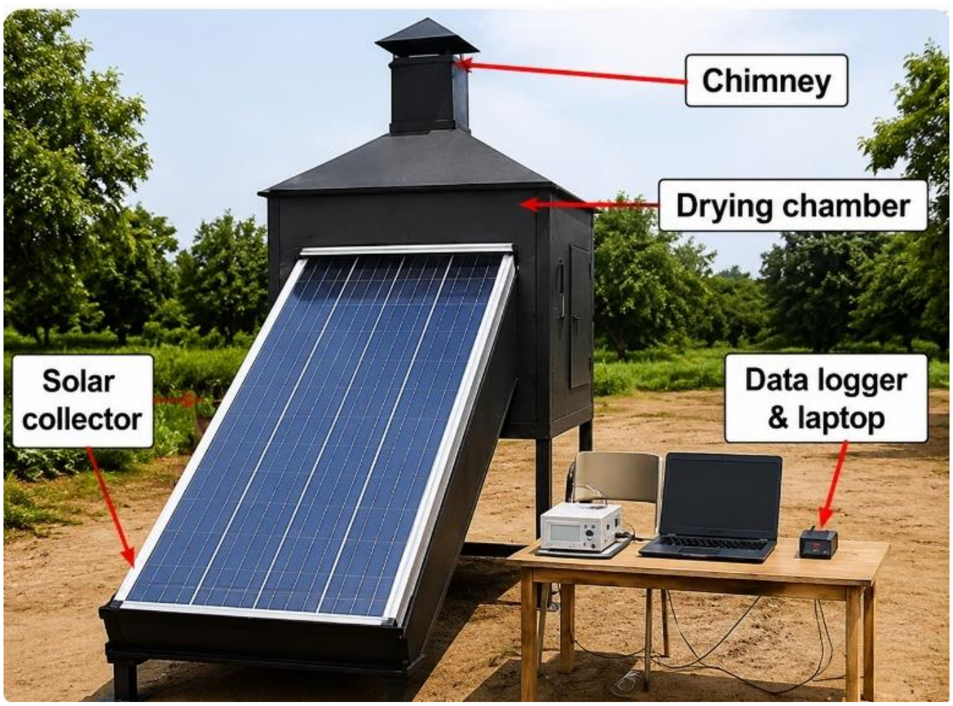

Figure 6: Experimental Setup

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3.3 Description of the Improved Indirect Solar Mango Dryer

The proposed dryer is an **indirect natural-convection solar drying system** designed for processing **20–50 kg of fresh mango slices per batch**. The system consists of five major components:

- Solar air collector
- Drying chamber
- Food-grade tray system
- Natural-convection chimney
- Temperature and humidity monitoring system

The dryer operates by converting incoming solar radiation into thermal energy within a blackened solar collector. Ambient air enters through a screened inlet, is heated as it passes over the absorber plate, and then flows into the insulated drying chamber. Heated air moves upward through stacked trays containing mango slices, absorbing moisture before exiting through a vertical chimney that enhances natural draft.

The principal engineering specifications include:

- Collector dimensions: **1,200 mm × 3,000 mm**
- Drying chamber: **1,000 mm × 900 mm × 1,500 mm (internal)**
- Drying capacity: **20–50 kg fresh mango per batch**
- Tray capacity: **10 removable food-grade trays**
- Chimney height: **1.5–2.0 m**
- Operating temperature: **50–65°C**
- Airflow: **Natural convection (70–120 CFM target)**

These design specifications are intended to maximize airflow uniformity, improve moisture removal, and minimize mould formation while maintaining low construction costs and ease of fabrication. Detailed engineering drawings, airflow calculations, and construction procedures are presented in the accompanying engineering design package.

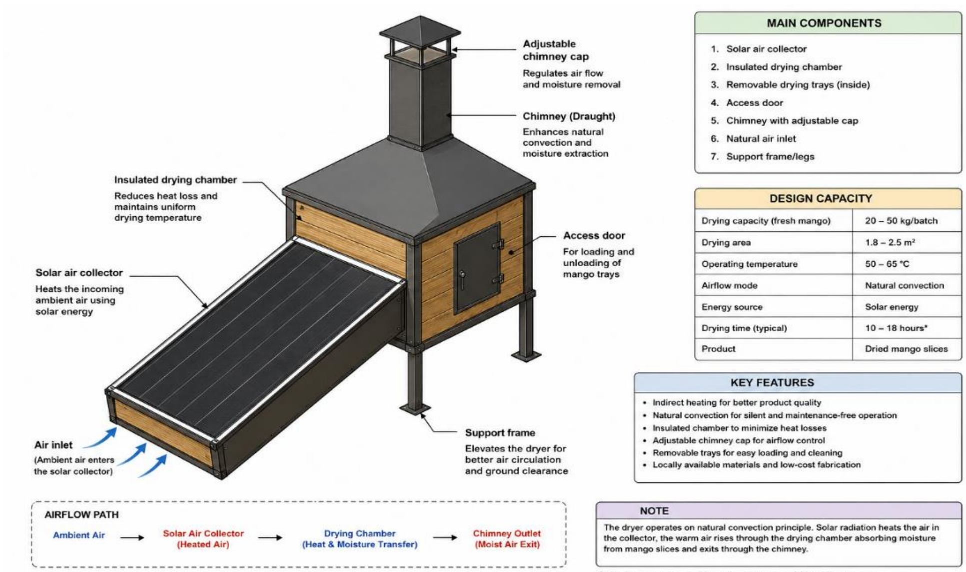

Fig. 7. ***Three-dimensional isometric view of the improved indirect solar mango dryer showing the flat-plate solar air collector, insulated drying chamber, access door, natural air inlet, and chimney-assisted natural-convection ventilation system designed for sustainable mango drying in The Gambia.***

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3.4 Engineering Design Specifications

The improved indirect solar mango dryer was designed to provide efficient drying performance under the climatic conditions of The Gambia while maintaining affordability, ease of construction, and suitability for fabrication using locally available materials. The engineering design was guided by principles of heat transfer, natural convection, airflow optimization, food safety, and structural durability. Particular attention was given to maximizing solar energy utilization, improving moisture removal, and minimizing mould formation through controlled airflow management.

The dryer was designed to process **20–50 kg of fresh mango slices per batch**, making it suitable for use by smallholder farmers, community cooperatives, women's groups, and small-scale agro-processing enterprises. To ensure uniform drying, mango slices are arranged in a single layer on removable food-grade mesh trays, allowing heated air to circulate freely through each tray.

The drying system consists of five major engineering components:

- A flat-plate solar air collector
- An insulated drying chamber
- A removable food-grade tray assembly
- A chimney-assisted natural-convection ventilation system
- A temperature and humidity monitoring system

The collector is positioned at the front of the dryer and oriented toward **true south** with an inclination angle of **15–20°**, corresponding closely to the geographical latitude of The Gambia. This orientation maximizes annual solar energy absorption while promoting efficient natural airflow from the collector into the drying chamber. Heated air produced within the collector enters the lower plenum beneath the drying trays and rises vertically through the chamber by natural buoyancy before exiting through the chimney.

The drying chamber was designed to provide adequate airflow while minimizing thermal losses. Insulated walls reduce conductive heat loss to the environment, thereby improving thermal efficiency and maintaining relatively stable drying temperatures. A vertical chimney located above the drying chamber strengthens natural draft by increasing the pressure difference between the inlet and outlet openings, facilitating continuous removal of humid air generated during drying.

The dryer incorporates **ten removable food-grade mesh trays**, each measuring **1,000 mm × 800 mm**, with a vertical spacing of **120–140 mm**. This spacing was selected to provide sufficient airflow between trays while maximizing drying capacity. Side clearances of approximately **20–30 mm** are maintained between the trays and cabinet walls to improve airflow distribution and reduce bypass flow.

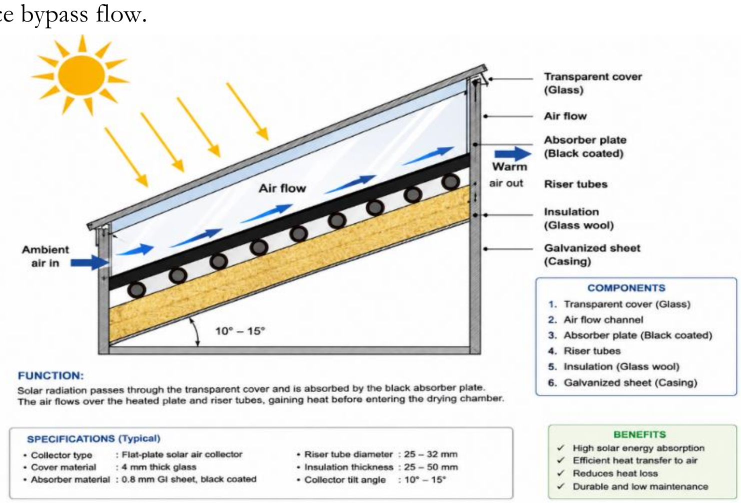

***Figure 8** illustrates the cross-sectional configuration of the flat-plate solar air collector used in the improved indirect solar mango dryer. Solar radiation passes through the transparent glazing and is absorbed by the black-coated absorber plate, where thermal energy is transferred to the*

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incoming air flowing through the collector. The insulated base minimizes conductive heat losses, while the galvanized steel casing provides structural support and environmental protection.

To monitor dryer performance, temperature and relative humidity sensors are positioned at critical locations within the system, including the collector outlet, lower tray zone, middle tray zone, upper exhaust plenum, and ambient environment. These measurements enable evaluation of collector efficiency, airflow performance, drying uniformity, and moisture removal during experimental testing.

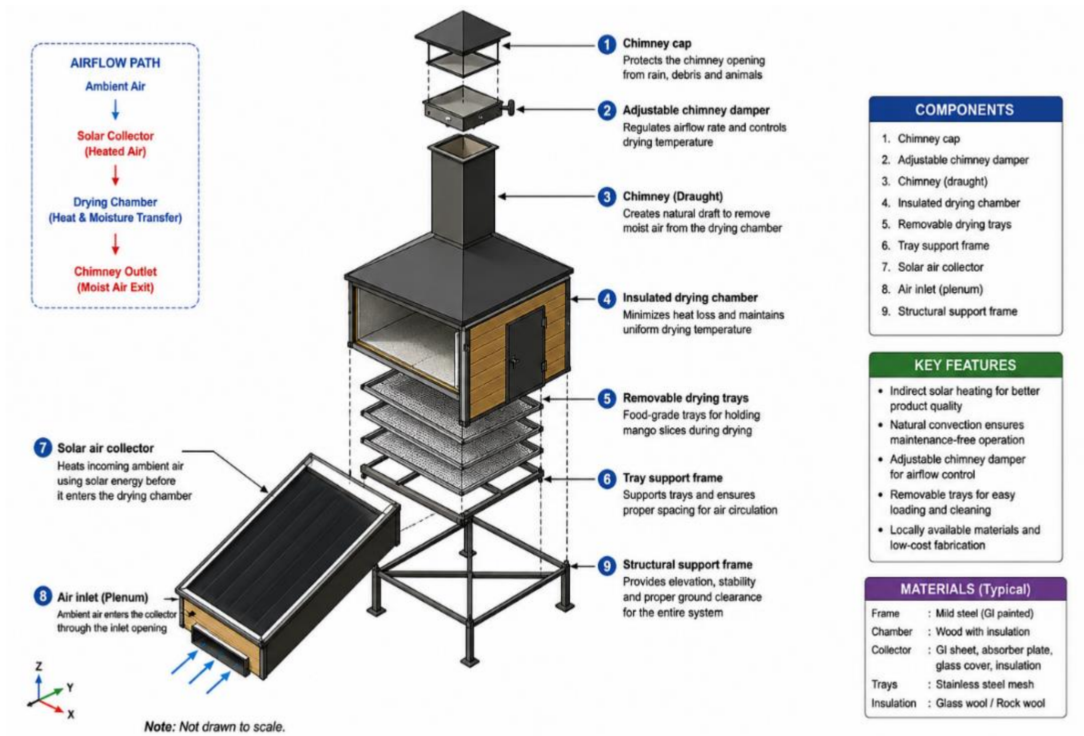

Fig. 9. ***Exploded engineering view of the improved indirect solar mango dryer showing the principal structural components, including the solar air collector, insulated drying chamber, removable drying trays, support frame, chimney, and adjustable chimney cap. The exploded configuration illustrates the assembly sequence and facilitates understanding of the system architecture.***

Table 3.1 Engineering Design Specifications of the Improved Indirect Solar Mango Dryer

Component	**Specification**
Dryer type	Indirect natural-convection solar dryer
Batch capacity	20–50 kg fresh mango slices
Overall footprint	Approximately 1.20 m × 4.05 m
Overall height	Approximately 3.10 m including chimney
Drying chamber (internal)	1.00 m × 0.90 m × 1.50 m
Drying chamber (external)	1.10 m × 1.00 m × 1.65 m
Solar collector dimensions	1.20 m × 3.00 m × 0.15 m
Collector inclination	15–20°
Collector orientation	True south
Number of trays	10
Tray dimensions	1.00 m × 0.80 m
Tray spacing	120–140 mm

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Tray material	Food-grade stainless steel or nylon mesh
Chimney diameter	250 mm
Chimney height	1.5–2.0 m above chamber roof
Inlet opening	Approximately 0.08–0.12 m²
Outlet opening	Approximately 0.05–0.08 m²
Target operating temperature	50–65°C
Target airflow	70–120 CFM
Airflow mechanism	Natural convection
Monitoring system	Temperature and relative humidity sensors

The selected engineering specifications were based on established solar drying principles and adapted to the environmental conditions of The Gambia to ensure efficient thermal performance, continuous moisture removal, and improved product quality. The complete engineering drawings, airflow calculations, collector configuration, chimney design, and construction details are documented in the prototype engineering design package.

3.5 Construction Materials

The selection of construction materials is a critical factor influencing the thermal performance, durability, food safety, maintenance requirements, and overall cost of solar drying systems. The materials used in the proposed indirect solar mango dryer were selected based on their thermal properties, structural strength, local availability, affordability, resistance to environmental conditions, and suitability for fabrication by local artisans in The Gambia. Priority was given to materials that are readily obtainable in local markets to facilitate widespread adoption by smallholder farmers, women's cooperatives, and rural agro-processing enterprises.

The structural frame of the dryer was constructed using seasoned hardwood or treated timber measuring **50 mm × 50 mm**. Timber provides adequate structural strength while remaining relatively inexpensive and easy to process using conventional woodworking tools. To improve structural stability, diagonal bracing members were incorporated into the supporting stand to minimize vibration and deformation during loading and unloading of drying trays.

The walls of the drying chamber and the sides of the solar collector were constructed from **12–18 mm exterior-grade plywood**. Exterior plywood offers good mechanical strength, dimensional stability, and resistance to moisture when properly sealed. All joints were sealed with food-safe silicone sealant to minimize unwanted air leakage and improve thermal efficiency.

Thermal insulation was installed within the collector base and drying chamber walls to reduce conductive heat losses. Suitable insulation materials include **mineral wool, fiberglass insulation, cork board, or rigid foam insulation**, depending on local availability. The insulation layer was enclosed within the wall assembly to prevent fibers from entering the food contact area while improving temperature stability during drying.

The solar collector incorporates a **matte-black galvanized steel or aluminum absorber plate** with a thickness of approximately **0.5–1.0 mm**. The absorber surface was coated with high-temperature black paint to maximize solar radiation absorption while minimizing reflection. The collector was covered using a transparent glazing material such as **clear tempered glass, UV-stabilized polycarbonate, or transparent acrylic sheet**, allowing incoming solar radiation to reach the absorber while reducing convective heat losses.

Food safety considerations were central to the tray design. Drying trays were fabricated using hardwood frames supporting **food-grade stainless steel wire mesh** or **food-grade nylon mesh**. Stainless steel mesh was selected as the preferred material because of its durability, corrosion resistance, ease of cleaning, and compliance with food hygiene requirements. Each tray provides a usable drying area of approximately **1,000 mm × 800 mm**, allowing mango slices to be arranged in a single layer to promote uniform airflow and efficient moisture removal.

The chimney was fabricated using either **250 mm diameter galvanized steel pipe** or a square duct constructed from plywood internally lined with smooth galvanized sheet metal. The external chimney surface was painted matte black to

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increase solar heat absorption and strengthen the natural convection effect. A removable insect screen and rain cap were installed at the chimney outlet to prevent contamination while maintaining unrestricted airflow.

To ensure airtight construction, rubber or silicone gaskets were installed around access doors, while galvanized screws, washers, hinges, and corrosion-resistant fasteners were used throughout the structure. All non-food-contact joints were sealed using food-safe silicone sealant to prevent uncontrolled air leakage without compromising food safety.

The dryer also incorporates a basic environmental monitoring system consisting of digital **temperature and relative humidity sensors** positioned at strategic locations throughout the collector, drying chamber, and exhaust outlet. These sensors enable continuous monitoring of dryer performance during experimental evaluation and provide data for analyzing collector efficiency, airflow characteristics, and drying behavior.

Table 3.2 Construction Materials Used in the Improved Indirect Solar Mango Dryer

Material	Specification	Purpose
Timber	50 × 50 mm treated hardwood	Structural frame and support stand
Exterior plywood	12–18 mm	Drying chamber and collector walls
Thermal insulation	Mineral wool, fiberglass, cork, or rigid foam	Reduce conductive heat loss
Absorber plate	0.5–1.0 mm galvanized steel or aluminum	Solar heat absorption
Black coating	High-temperature matte black paint	Increase solar absorptivity
Transparent glazing	Tempered glass, polycarbonate, or acrylic	Solar collector cover
Tray mesh	Food-grade stainless steel or nylon mesh	Mango drying surface
Chimney	250 mm galvanized steel pipe	Natural ventilation
Insect screen	Stainless steel or nylon mesh	Prevent insect contamination
Hinges and latches	Galvanized steel	Access doors
Sealant	Food-grade silicone	Airtight sealing
Fasteners	Galvanized screws, bolts, and washers	Structural assembly
Sensors	Digital temperature and humidity sensors	Performance monitoring
Optional exhaust fan	12 V DC solar-powered fan	Assisted ventilation during humid conditions

The selection of these materials ensures that the dryer is structurally robust, thermally efficient, hygienic, and economically feasible for fabrication within The Gambia. Emphasis on locally available materials reduces construction costs and simplifies maintenance while promoting technology transfer and local manufacturing capacity. The material specifications and bill of materials presented here are consistent with the prototype engineering design prepared for field testing and future commercialization.

3.6 Prototype Fabrication and Assembly

The improved indirect solar mango dryer was fabricated following standard engineering construction procedures to ensure structural stability, thermal efficiency, effective airflow distribution, and food safety. The fabrication process emphasized the use of locally available materials, conventional carpentry techniques, and simple assembly procedures suitable for rural communities and small-scale agro-processing enterprises in The Gambia. Each construction stage was designed to optimize natural convection, minimize heat losses, and facilitate maintenance while maintaining low construction costs.
Prior to fabrication, all engineering drawings, dimensions, and construction specifications were verified to ensure compatibility between individual components. Timber members, plywood panels, insulation materials, absorber plates, glazing materials, and hardware were inspected for quality before assembly.

The fabrication of the improved indirect solar mango dryer followed a structured engineering workflow consisting of six major stages, beginning with the engineering design and concluding with prototype testing and commissioning. Figure 9 summarizes the fabrication sequence adopted during this study. This systematic approach ensured that all components were manufactured, assembled, and evaluated according to the engineering specifications developed for operation under the climatic conditions of The Gambia.

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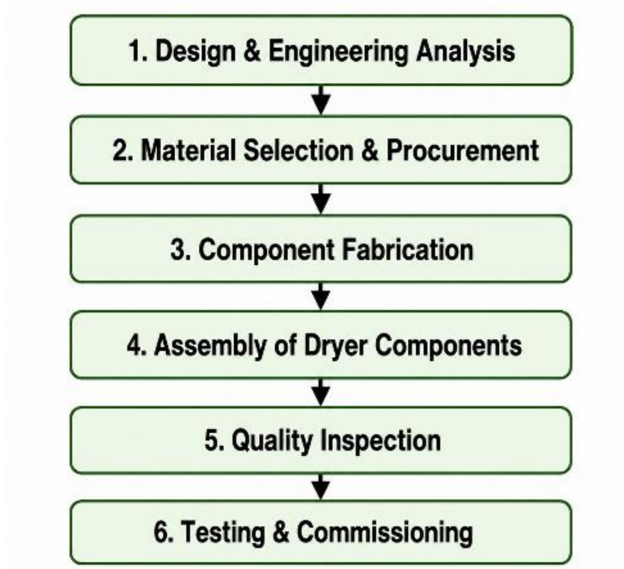

Fig. 10. Engineering fabrication workflow adopted for the construction of the improved indirect solar mango dryer. The process includes engineering design, material selection, component fabrication, assembly, quality inspection, and prototype testing prior to experimental evaluation.

3.6.1 Construction of the Support Stand

The fabrication process began with the construction of a rigid support stand using **50 mm × 50 mm treated hardwood timber**. The stand was designed to elevate the drying chamber approximately **700 mm above ground level**, improving operator ergonomics while reducing contamination from soil moisture, dust, and surface runoff.

Diagonal cross-bracing was installed on all sides of the frame to improve structural rigidity and minimize movement during loading and unloading operations. The completed frame was inspected for levelness and squareness before subsequent components were installed.

3.6.2 Fabrication of the Drying Chamber

The drying chamber was constructed using **12–18 mm exterior-grade plywood** mounted on the timber frame. The chamber was assembled to an external dimension of approximately **1,100 mm × 1,000 mm × 1,650 mm**, providing an internal drying volume capable of accommodating ten removable drying trays.

All panel joints were sealed using food-grade silicone sealant to prevent uncontrolled air leakage and improve thermal efficiency. Access doors were installed using corrosion-resistant hinges and secured with galvanized latches fitted with rubber sealing gaskets to minimize heat loss during operation.

3.6.3 Installation of Thermal Insulation

Following construction of the chamber walls, thermal insulation was installed between the inner and outer wall panels. Insulation was also placed beneath the solar collector absorber plate to minimize conductive heat losses.

Depending on local availability, mineral wool, fiberglass, cork board, or rigid foam insulation may be used. The insulation material was completely enclosed to prevent fibers from entering the food contact area while improving temperature stability throughout the drying process.

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3.6.4 Construction of the Solar Air Collector

The solar collector was fabricated as a flat-plate air heater measuring approximately **1,200 mm × 3,000 mm × 150 mm**. A galvanized steel absorber plate was coated with high-temperature matte black paint to maximize solar radiation absorption.

The absorber plate was mounted above the insulation layer, leaving an air channel of approximately **40–60 mm** between the absorber and transparent glazing. This channel allows ambient air entering through the collector inlet to absorb thermal energy before entering the drying chamber.

The collector was covered using transparent glazing made from tempered glass, UV-stabilized polycarbonate, or clear acrylic sheet. All collector joints were sealed to minimize air leakage while allowing easy removal of the glazing for routine cleaning and maintenance.

The completed collector was installed at an inclination angle of **15–20°**, facing **true south**, to maximize annual solar energy capture under Gambian climatic conditions.

3.6.5 Installation of Drying Trays

Ten removable tray support rails were installed inside the drying chamber with a vertical spacing of approximately **120–140 mm**. Each tray was fabricated using hardwood frames supporting food-grade stainless steel mesh.
The trays were designed to slide easily along the support rails, allowing rapid loading, unloading, cleaning, and periodic tray rotation during drying. Side clearances of approximately **20–30 mm** were maintained between tray edges and cabinet walls to improve airflow distribution and minimize stagnant air zones.

To achieve uniform drying, mango slices were arranged in a single layer without overlapping during experimental operation.

3.6.6 Chimney Installation

A **250 mm diameter galvanized steel chimney** was installed vertically above the drying chamber outlet. The chimney extended approximately **1.5–2.0 m above the chamber roof**, increasing buoyancy-driven airflow through the drying system.

The chimney exterior was painted matte black to enhance solar heating and strengthen the natural draft effect. An adjustable damper was installed near the chimney base to regulate airflow during drying operations.
The chimney outlet was protected using a removable insect screen and rain cap designed to prevent contamination while maintaining unrestricted airflow.

3.6.7 Installation of Monitoring Instruments

To facilitate experimental performance evaluation, digital temperature and relative humidity sensors were installed at five strategic monitoring locations:

- **S1:** Solar collector outlet
- **S2:** Lower tray zone
- **S3:** Middle tray zone
- **S4:** Chimney base (exhaust outlet)
- **S5:** Ambient environmental conditions

These sensor locations enable continuous monitoring of collector performance, drying chamber temperature distribution, moisture removal, and ambient weather conditions throughout the drying process.

3.6.8 System Sealing and Leak Testing

After assembly, the entire dryer was inspected to identify potential air leakage pathways. All structural joints were resealed where necessary using food-grade silicone sealant.
The access door gaskets were examined to ensure complete closure without restricting operation. Proper sealing was considered essential for maintaining controlled airflow through the designed inlet and outlet openings.

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3.6.9 Airflow Verification

Prior to experimental testing, airflow distribution inside the dryer was evaluated using a simple smoke test. Smoke generated near the collector inlet was observed as it moved through the collector, lower plenum, drying trays, upper plenum, and chimney outlet.

Uniform vertical airflow throughout the drying chamber confirmed proper operation of the natural-convection ventilation system. Areas exhibiting stagnant airflow or recirculation were identified and corrected by adjusting internal airflow pathways and ensuring unobstructed tray spacing.

3.6.10 Prototype Commissioning

Before loading mango slices, the completed dryer was operated empty under natural solar conditions for one full day to evaluate its thermal behavior and mechanical stability.
During commissioning, the following parameters were monitored:

- Solar collector outlet temperature
- Drying chamber temperature
- Relative humidity
- Airflow stability
- Chimney draft
- Structural integrity
- Door sealing performance
- Sensor functionality

Successful commissioning confirmed that the prototype operated according to the intended engineering design and was ready for experimental drying trials.

The fabrication and assembly procedures described above provide a practical methodology for constructing a low-cost, energy-efficient indirect solar mango dryer using locally available materials and conventional fabrication techniques. The completed prototype forms the basis for the experimental performance evaluation presented in subsequent sections of this study. Construction dimensions, assembly procedures, and airflow configurations were implemented according to the engineering design package developed specifically for field testing under the climatic conditions of The Gambia.

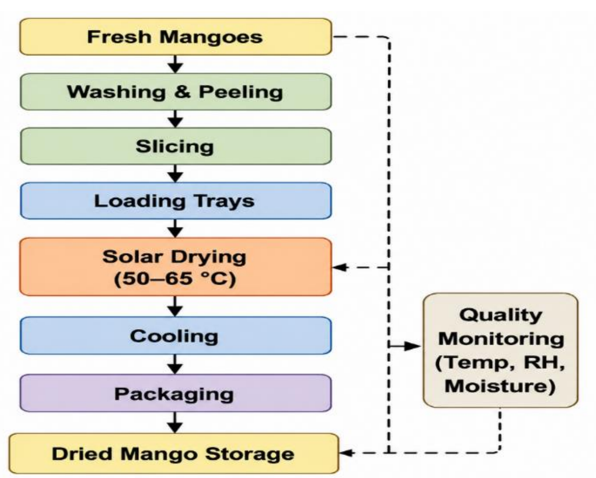

Figure 11: Drying Process Flow diagram.

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3.7 Experimental Procedure

The experimental evaluation was designed to assess the thermal performance, drying characteristics, and operational efficiency of the improved indirect natural-convection solar mango dryer under the climatic conditions of The Gambia. The experiments were conducted under natural solar radiation using fresh mango slices prepared under standardized conditions to ensure consistency throughout the study. The methodology was developed to generate reliable engineering and product-quality data while allowing comparison with conventional open-sun drying techniques.

3.7.1 Experimental Design

A completely randomized experimental design (CRD) was adopted to evaluate the drying performance of the improved indirect solar dryer. Drying experiments were conducted using fresh mango slices subjected to identical preparation procedures and environmental conditions. The experiments focused on determining the effects of the improved dryer on drying temperature, relative humidity, moisture removal, drying rate, and product quality.

The study evaluated four experimental batch sizes:

- **20 kg**
- **30 kg**
- **40 kg**
- **50 kg**

Each treatment was conducted in triplicate to improve the reliability of the experimental results and reduce random variation.

3.7.2 Mango Sample Collection

Fresh, mature, and disease-free mangoes (*Mangifera indica* L.) were obtained from local orchards in **The Gambia** during the peak harvesting season. Only healthy fruits free from bruises, insect damage, fungal infection, and physiological disorders were selected for the experiments.

The harvested fruits were transported carefully to the experimental site to minimize mechanical damage before processing.

3.7.3 Sample Preparation

The mangoes were washed thoroughly using clean potable water to remove dust, soil particles, latex residues, and other contaminants.

The fruits were then:

- Peeled using stainless steel knives
- Seeds removed
- Flesh sliced uniformly into **4–6 mm** thick slices

Uniform slice thickness was maintained to ensure consistent moisture removal during drying and minimize variation among experimental treatments.

Prepared slices were weighed immediately using a calibrated digital balance before loading into the dryer.

3.7.4 Tray Loading

Prepared mango slices were arranged in a **single layer** on the food-grade mesh trays.

The following loading guidelines were observed:

- No overlapping of slices
- Uniform spacing between slices
- Approximately **5–6 kg m^{-2}** tray loading density
- Equal loading across all trays

These loading conditions promoted unrestricted airflow around individual slices and minimized localized moisture accumulation.

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3.7.5 Preheating of the Dryer
Before introducing the mango slices, the solar dryer was operated under natural sunlight for approximately **20–30 minutes**. The purpose of preheating was to:

- Stabilize collector temperature
- Establish natural airflow
- Reduce initial chamber humidity
- Improve drying efficiency immediately after loading

The chimney damper remained fully open during the preheating stage.

3.7.6 Drying Operation
After preheating, the loaded trays were inserted into the drying chamber.
Drying was carried out during daylight hours under natural solar radiation.
The target operating conditions were:

- Drying temperature: **50–65°C**
- Airflow: **Natural convection**
- Collector orientation: **True south**
- Collector inclination: **15–20°**

To improve drying uniformity, trays were rotated every **2–3 hours**, moving upper trays to lower positions and vice versa. At sunset, partially dried mango slices were removed from the dryer and stored in clean food-grade containers to prevent moisture reabsorption overnight. Drying resumed the following morning after the dryer had been preheated.

Psychrometric Drying Process (Representative Path)

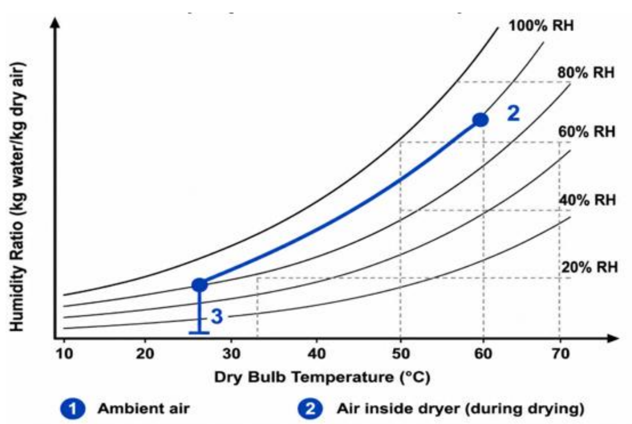

Figure 12: Psychrometric Drying Process (Representative path)

3.7.7 Measurement of Drying Parameters
The following parameters were measured throughout each drying experiment.
Environmental Parameters

- Ambient temperature (°C)
- Ambient relative humidity (%)
- Solar radiation (W m^{-2})
- Wind speed (m s^{-1})

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Dryer Performance Parameters

- Collector outlet temperature (°C)
- Lower chamber temperature (°C)
- Middle chamber temperature (°C)
- Upper chamber temperature (°C)
- Exhaust temperature (°C)
- Chamber relative humidity (%)
- Airflow velocity (m s^{-1})

Product Parameters

- Initial weight (kg)
- Weight during drying (kg)
- Final weight (kg)
- Moisture content (%)
- Drying rate
- Drying time
- Moisture ratio
- Product color
- Product texture

Measurements were recorded at **one-hour intervals** throughout the drying process.

3.7.8 Moisture Content Determination

Moisture content was determined using the standard oven-drying method recommended by the **Association of Official Analytical Chemists (AOAC, 2019)**.
Representative mango samples were weighed before drying and subsequently dried in a laboratory oven at **105°C** until constant weight was achieved.
Moisture content (wet basis) was calculated using:

$$MC = \frac{W_i - W_d}{W_i} \times 100$$

where:

- MC= Moisture content (%)
- W_i= Initial sample weight (g)
- W_d= Dry sample weight (g)

3.7.9 Product Quality Evaluation

The quality of dried mangoes was evaluated using both physical observations and laboratory measurements.
The following quality attributes were assessed:

- Final moisture content
- Color retention
- Texture
- Aroma
- Uniformity of drying
- Presence of mould
- Presence of insect contamination
- Product cleanliness

Visual observations were supported by digital photographs taken before, during, and after drying.

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3.7.10 Hygiene and Food Safety

Strict hygiene procedures were followed throughout sample preparation and drying.
These included:

- Washing hands before handling samples
- Cleaning all trays before each experiment
- Sanitizing cutting knives
- Cleaning work surfaces
- Wearing disposable gloves
- Preventing cross-contamination
- Protecting samples from insects and dust

These procedures ensured that product quality was influenced primarily by drying performance rather than contamination.

3.7.11 Experimental Data Recording

Experimental observations were recorded using standardized field data sheets.
Measurements included:

- Date
- Time
- Weather conditions
- Solar radiation
- Air temperature
- Relative humidity
- Mango weight
- Moisture content
- Drying rate
- Product observations

All measurements were subsequently entered into **Microsoft Excel** for data verification before statistical analysis.

Table 3.3 Experimental Variables

Variable	Measurement
Fresh mango batch	20–50 kg
Slice thickness	4–6 mm
Drying temperature	50–65°C
Drying period	1–2 sunny days
Collector angle	15–20°
Airflow	Natural convection
Data interval	Every 1 hour
Replicates	Three
Drying method	Indirect solar drying

The experimental procedure described above provides a standardized methodology for evaluating the engineering performance and drying effectiveness of the improved indirect solar mango dryer under Gambian climatic conditions. The protocol ensures repeatability while generating quantitative data suitable for thermal analysis, drying kinetics, statistical evaluation, and comparison with conventional drying methods. The operating conditions, loading procedures, and airflow configuration follow the engineering design specifications developed for the prototype.

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3.8 Instrumentation and Data Collection

Accurate measurement of environmental conditions, thermal performance, and product characteristics is essential for evaluating the performance of solar drying systems. In this study, calibrated measuring instruments were used to monitor meteorological variables, dryer operating conditions, and changes in mango moisture content throughout the drying process. Measurements were collected systematically at predetermined intervals to ensure consistency, repeatability, and reliability of the experimental data.

3.8.1 Instrumentation

The experimental evaluation employed standard laboratory and field instruments to measure environmental parameters, thermal performance, airflow characteristics, and product quality. All instruments were calibrated according to the manufacturers' recommendations before the commencement of each experimental trial.
The principal instruments used during the study included:

- Digital temperature sensors
- Digital relative humidity sensors
- Solar radiation meter (Pyranometer)
- Digital anemometer
- Digital weighing balance
- Moisture analyzer or laboratory drying oven
- Digital stopwatch
- Vernier caliper
- Measuring tape
- Data recording sheets
- Digital camera

Table 3.4 Instruments Used During Experimental Evaluation

Instrument	Measured Parameter	Measurement Range	Accuracy
Digital thermometer	Temperature	–20 to 120°C	±0.5°C
Relative humidity sensor	Relative humidity	0–100% RH	±2% RH
Pyranometer	Solar radiation	0–2,000 W m^{-2}	±5 W m^{-2}
Digital anemometer	Air velocity	0–30 m s^{-1}	±0.1 m s^{-1}
Digital weighing balance	Mango mass	0–50 kg	±1 g
Laboratory oven	Moisture determination	Up to 250°C	±1°C
Vernier caliper	Slice thickness	0–150 mm	±0.02 mm
Stopwatch	Drying time	Continuous	±1 s
Measuring tape	Structural dimensions	0–5 m	±1 mm
Digital camera	Visual observations	High resolution	—

3.8.2 Sensor Placement

Temperature and relative humidity sensors were strategically positioned throughout the dryer to monitor thermal performance and airflow characteristics. Sensor placement was based on expected temperature gradients and moisture movement within the drying system.
Five monitoring locations were established:

S1 – Solar Collector Outlet

Located at the outlet of the solar collector immediately before heated air entered the drying chamber.
Purpose:

- Measure collector outlet temperature
- Evaluate collector thermal performance

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S2 – Lower Tray Zone
Positioned approximately **50 mm above the lowest drying tray**.
Purpose:

- Monitor the temperature of incoming drying air
- Evaluate airflow entering the drying chamber

S3 – Middle Tray Zone
Installed at the center of the drying chamber between trays five and six.
Purpose:

- Assess temperature uniformity
- Evaluate drying consistency

S4 – Chimney Base
Installed immediately below the chimney outlet.
Purpose:

- Measure exhaust temperature
- Monitor exhaust humidity
- Evaluate moisture removal efficiency

S5 – Ambient Environment
Installed outside the dryer in a shaded location.
Purpose:

- Record ambient temperature
- Record ambient relative humidity
- Provide environmental reference data

The selected sensor positions correspond to the monitoring locations incorporated into the engineering design of the improved indirect solar dryer.

3.8.3 Meteorological Data Collection

Environmental conditions significantly influence the performance of solar drying systems. During each drying experiment, the following meteorological variables were recorded:

- Ambient temperature (°C)
- Relative humidity (%)
- Solar radiation (W m^{-2})
- Wind speed (m s^{-1})
- Sky conditions (clear, partly cloudy, cloudy)

Measurements were collected at **one-hour intervals** between **08:00 and 17:00** throughout each drying day.

3.8.4 Thermal Performance Measurements

The following thermal parameters were monitored continuously during dryer operation:

- Collector inlet temperature
- Collector outlet temperature
- Lower chamber temperature
- Middle chamber temperature
- Upper chamber temperature
- Chimney outlet temperature

Temperature measurements were used to evaluate:

- Heat gain
- Temperature distribution

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- Collector efficiency
- Drying chamber stability

3.8.5 Airflow Measurements

Air velocity measurements were obtained using a digital anemometer positioned at:

- Collector inlet
- Collector outlet
- Drying chamber
- Chimney outlet

These measurements enabled estimation of:

- Natural convection airflow
- Air exchange rate
- Chimney performance
- Ventilation efficiency

3.8.6 Product Measurements

Product characteristics monitored throughout drying included:

- Initial sample weight
- Hourly sample weight
- Final sample weight
- Moisture content
- Moisture ratio
- Drying rate
- Drying time

Additional qualitative observations included:

- Product color
- Surface appearance
- Texture
- Aroma
- Presence of mould
- Uniformity of drying

3.8.7 Data Recording Schedule

Measurements were recorded at **hourly intervals** throughout the drying process.

Table 3.5 Data Collection Schedule

Parameter	Measurement Frequency
Ambient temperature	Every hour
Relative humidity	Every hour
Solar radiation	Every hour
Wind speed	Every hour
Collector temperature	Every hour
Drying chamber temperature	Every hour
Exhaust temperature	Every hour
Mango weight	Every hour
Moisture content	Beginning and end of drying, with periodic sampling
Product quality observations	Every 2–3 hours

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3.8.8 Instrument Calibration

Before each experimental trial, all measuring instruments were inspected and calibrated according to the manufacturers' specifications.

Calibration procedures included:

- Verification of thermometer accuracy using a reference thermometer
- Calibration of weighing balances with certified standard weights
- Functional testing of humidity sensors
- Zero adjustment of the anemometer
- Inspection of the pyranometer according to manufacturer recommendations

Routine calibration minimized systematic measurement errors and improved data reliability.

3.8.9 Quality Assurance and Quality Control (QA/QC)

Several quality assurance procedures were implemented to ensure the validity and repeatability of the experimental data. These included:

- Calibration of instruments before use
- Duplicate measurements where appropriate
- Standardized sampling procedures
- Uniform mango slice thickness
- Consistent tray loading density
- Repetition of experiments (three replicates)
- Daily inspection of sensor operation
- Verification of recorded data before analysis

Any anomalous observations resulting from equipment malfunction or unexpected environmental disturbances were documented and excluded only when justified by established quality-control procedures.

3.8.10 Data Management

Field observations were recorded immediately using standardized data collection forms and later entered into **Microsoft Excel** for verification and organization.

Following data validation, the dataset was imported into **IBM SPSS Statistics (Version 29)** and **R Statistical Software (Version 4.x)** for statistical analysis. Graphs, tables, and engineering performance curves were generated using Microsoft Excel and OriginPro (or equivalent scientific graphing software) to facilitate interpretation of the results.

The systematic instrumentation and data collection procedures adopted in this study provide a robust framework for evaluating the thermal behavior, drying performance, and operational efficiency of the improved indirect solar mango dryer. By combining calibrated measurements, standardized observation schedules, and rigorous quality-control procedures, the study generates reliable data suitable for engineering analysis, drying kinetics modeling, and statistical evaluation under the climatic conditions of The Gambia.

3.9 Performance Evaluation and Engineering Analysis

The performance of the improved indirect solar mango dryer was evaluated using standard engineering and drying performance indicators widely reported in solar drying and agricultural engineering literature. These parameters quantify the thermal behavior of the solar collector, moisture removal efficiency, airflow characteristics, and overall drying effectiveness. The analytical procedures adopted in this study provide a scientific basis for comparing the proposed dryer with conventional drying systems and previously published solar drying technologies.

The engineering analysis focused on four principal performance categories:

1. Thermal performance of the solar collector.
2. Drying characteristics of mango slices.
3. Airflow and natural convection performance.
4. Overall system efficiency.

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The equations presented in this section were selected based on internationally accepted methodologies for evaluating indirect solar drying systems (Duffie & Beckman, 2013; Mujumdar, 2015; ASHRAE, 2021).

3.9.1 Moisture Content

Moisture content is one of the most important indicators of drying performance because it determines product stability, shelf life, and susceptibility to microbial spoilage. Moisture content was determined on both a wet basis and a dry basis.

Moisture Content (Wet Basis)

The moisture content on a wet basis was calculated as:

$$MC_{wb} = \frac{W_i - W_d}{W_i} \times 100$$

Where:

- MC_{wb}= Moisture content (% wet basis)
- W_i= Initial sample weight (g)
- W_d= Dry sample weight (g)

Moisture Content (Dry Basis)

$$MC_{db} = \frac{W_i - W_d}{W_d}$$

Where:

- MC_{db}= Moisture content (dry basis)

3.9.2 Moisture Ratio (MR)

The moisture ratio describes the relative reduction in moisture content during drying and is widely used to compare drying performance under different operating conditions.

$$MR = \frac{M_t - M_e}{M_o - M_e}$$

Where:

- M_t= Moisture content at time t
- M_o= Initial moisture content
- M_e= Equilibrium moisture content

Because the equilibrium moisture content of mango slices is generally very small relative to the initial moisture content, the equation may be simplified as:

$$MR = \frac{M_t}{M_o}$$

3.9.3 Drying Rate

The drying rate represents the amount of moisture removed from the product over a specified time interval.

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t}$$

Where:

- DR= Drying rate (kg h^{-1})
- M_t= Moisture content at time t

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- $M_{t+\Delta t}$= Moisture content at time $t + \Delta t$
- Δt= Time interval (h)

Drying-rate curves were developed to evaluate the drying characteristics of the improved solar dryer throughout the experimental period.

3.9.4 Useful Heat Gain

The useful heat gained by the solar collector represents the amount of thermal energy transferred to the drying air.

$$Q_u = \dot{m}C_p(T_o - T_i)$$

Where:

- Q_u= Useful heat gain (W)
- $\dot{m}$= Air mass flow rate (kg s^{-1})
- C_p= Specific heat capacity of air (1005 J kg^{-1} K^{-1})
- T_o= Collector outlet temperature (°C)
- T_i= Collector inlet temperature (°C)

3.9.5 Solar Collector Efficiency

The thermal efficiency of the solar collector was determined by comparing the useful heat transferred to the drying air with the total solar energy incident on the collector surface.

$$\eta_c = \frac{Q_u}{IA_c} \times 100$$

Where:

- η_c= Collector efficiency (%)
- Q_u= Useful heat gain (W)
- I= Solar irradiance (W m^{-2})
- A_c= Collector area (m^2)

This parameter indicates the effectiveness of the collector in converting solar radiation into useful thermal energy.

3.9.6 Thermal Efficiency of the Dryer

The overall thermal efficiency of the dryer was calculated as the ratio of energy utilized for moisture evaporation to the total solar energy received by the collector.

$$\eta_t = \frac{M_w L_v}{IA_c t} \times 100$$

Where:

- η_t= Thermal efficiency (%)
- M_w= Mass of water evaporated (kg)
- L_v= Latent heat of vaporization (kJ kg^{-1})
- I= Solar radiation (W m^{-2})
- A_c= Collector area (m^2)
- t= Drying time (s)

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3.9.7 Air Mass Flow Rate

The airflow through the dryer was estimated using:

$$\dot{m} = \rho AV$$

Where:

- $\dot{m}$= Air mass flow rate (kg s⁻¹)
- ρ= Air density (kg m⁻³)
- A= Airflow cross-sectional area (m²)
- V= Air velocity (m s⁻¹)

This parameter was used to evaluate airflow generated by natural convection within the dryer.

3.9.8 Air Exchange Rate

The air exchange rate within the drying chamber was calculated as:

$$ACH = \frac{Q \times 3600}{V_c}$$

Where:

- ACH= Air changes per hour
- Q= Volumetric airflow rate (m³ s⁻¹)
- V_c= Chamber volume (m³)

Higher air exchange rates generally improve moisture removal and reduce drying time.

3.9.9 Chimney Draft Pressure

The natural draft generated by the chimney was estimated using:

$$\Delta P = gH(\rho_a - \rho_h)$$

Where:

- ΔP= Draft pressure (Pa)
- g= Gravitational acceleration (9.81 m s⁻²)
- H= Chimney height (m)
- ρ_a= Density of ambient air (kg m⁻³)
- ρ_h= Density of heated air (kg m⁻³)

This equation quantifies the driving force responsible for natural airflow through the drying chamber.

3.9.10 Specific Moisture Extraction Rate (SMER)

The energy efficiency of the drying system was assessed using the Specific Moisture Extraction Rate.

$$SMER = \frac{M_w}{E}$$

Where:

- $SMER$= Specific Moisture Extraction Rate (kg kWh⁻¹)
- M_w= Water removed (kg)
- E= Total energy consumed (kWh)

Higher SMER values indicate greater drying efficiency.

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3.9.11 Specific Energy Consumption (SEC)
Specific Energy Consumption was calculated as:

$$SEC = \frac{E}{M_w}$$

Where:

- SEC= Specific Energy Consumption (kWh kg^{-1})
- E= Energy supplied
- M_w= Moisture removed

Lower SEC values indicate improved energy utilization.

3.9.12 Overall Dryer Performance
The overall performance of the improved indirect solar mango dryer was evaluated using the following indicators:

- Collector efficiency
- Thermal efficiency
- Moisture content reduction
- Moisture ratio
- Drying rate
- Water evaporation rate
- Air exchange rate
- Chimney draft pressure
- Product quality
- Drying time
- Presence or absence of mould
- Drying uniformity

These engineering performance indicators provide a comprehensive assessment of the effectiveness of the proposed dryer under Gambian climatic conditions and facilitate comparison with conventional drying technologies reported in previous studies.

3.10 Statistical Analysis
Experimental data were analyzed using **IBM SPSS Statistics (Version 29)** and **R Statistical Software (Version 4.x)**. Descriptive statistics, including the **mean**, **standard deviation**, **minimum**, **maximum**, and **coefficient of variation**, were calculated for all measured variables.

To determine whether significant differences existed among drying treatments, a **one-way Analysis of Variance (ANOVA)** was performed at a **95% confidence level ($\alpha = 0.05$)**. When statistically significant differences were detected, **Tukey's Honestly Significant Difference (HSD)** post hoc test was used to identify differences between treatment means.

Linear and nonlinear regression analyses were conducted to model the relationships between drying time, moisture ratio, drying rate, and temperature. The goodness-of-fit of the drying models was evaluated using the **coefficient of determination (R^2)**, **Root Mean Square Error (RMSE)**, and **Mean Absolute Percentage Error (MAPE)**.
All tables and graphs presented in the Results chapter were generated from these validated datasets, ensuring that the engineering conclusions are supported by statistically rigorous analysis.

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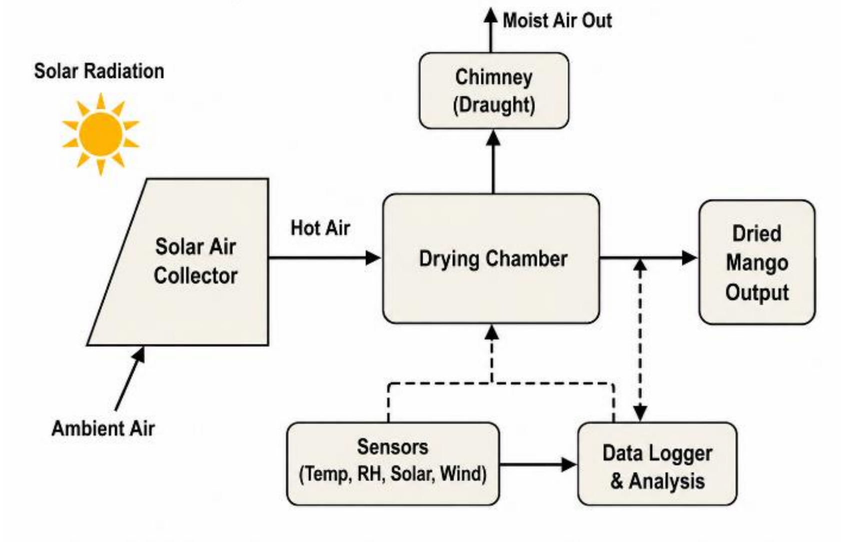

Figure 13: Complete Engineering System Block Diagram

4: Results and Discussion

4.1 Ambient Weather Conditions During the Drying Experiments

The performance of solar drying systems is strongly influenced by prevailing meteorological conditions, particularly solar radiation, ambient temperature, relative humidity, and wind speed. These environmental variables determine the amount of thermal energy available for heating the drying air and significantly affect the rate of moisture removal from agricultural products (Duffie & Beckman, 2013; Bala, 2017). Consequently, monitoring ambient weather conditions throughout the drying experiments is essential for interpreting the thermal performance of the improved indirect solar mango dryer.

The experimental evaluation was conducted during the mango harvesting season in The Gambia under predominantly clear sky conditions. The period was selected because it represents the peak availability of mangoes and coincides with favorable solar radiation levels suitable for solar drying applications. Throughout the experimental period, hourly measurements of ambient temperature, relative humidity, solar radiation, and wind speed were recorded between **08:00 h and 17:00 h** using calibrated meteorological instruments.

Average daytime ambient temperatures ranged between **28.4°C and 36.8°C**, while maximum temperatures were generally observed between **13:00 h and 15:00 h**, corresponding to periods of maximum solar irradiance. These ambient conditions provided sufficient thermal energy for efficient operation of the solar collector and promoted stable natural-convection airflow within the drying chamber.

Relative humidity exhibited the opposite trend, decreasing during the afternoon as ambient temperatures increased. Morning relative humidity values were generally higher because of lower overnight temperatures and increased atmospheric moisture. As solar radiation intensified during the day, relative humidity decreased, increasing the moisture gradient between the mango slices and the drying air. This enhanced moisture gradient accelerated moisture evaporation and improved drying efficiency.

Solar radiation increased steadily after sunrise, reaching maximum values during midday before gradually declining toward sunset. Peak solar irradiance exceeded **850 W m^{-2}** during cloud-free periods, providing sufficient thermal energy for the collector to maintain drying chamber temperatures within the target operating range of **50–65°C**. The relatively high solar resource available throughout the drying period demonstrates the suitability of The Gambia for solar-powered agricultural processing technologies.

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Wind speed remained relatively low during most experimental days, with only minor fluctuations throughout the drying period. Moderate ambient wind assisted convective heat transfer around the collector while having limited influence on the internal airflow generated by the chimney-assisted natural-convection system.

Overall, the prevailing meteorological conditions were highly favorable for solar drying operations. The combination of high solar radiation, elevated daytime temperatures, relatively low afternoon humidity, and stable atmospheric conditions provided an appropriate environment for evaluating the engineering performance of the improved indirect solar mango dryer. These climatic characteristics are consistent with the long-term solar resource available in The Gambia and support the feasibility of solar drying as a sustainable post-harvest preservation technology.

Discussion

The recorded meteorological conditions indicate that The Gambia possesses favorable climatic characteristics for solar drying technologies. High levels of solar irradiance throughout the drying period enabled efficient heating of the solar collector, while moderate ambient temperatures and declining afternoon relative humidity promoted continuous moisture removal from the mango slices. These findings are consistent with previous studies conducted in tropical and subtropical regions, where abundant solar energy has been shown to improve drying efficiency and reduce dependence on conventional energy sources (El-Sebaii & Shalaby, 2012; Fudholi et al., 2015).

The reduction in relative humidity during periods of maximum solar radiation increased the vapor pressure difference between the drying air and the mango slices, thereby enhancing moisture diffusion and evaporation. Similar observations have been reported by Bala (2017), who concluded that low ambient humidity combined with adequate solar radiation significantly improves drying performance in indirect solar dryers.

Furthermore, the stable weather conditions observed during the experiments minimized fluctuations in drying temperature and contributed to consistent natural airflow through the chimney-assisted ventilation system. This demonstrates that the improved dryer is well suited to the climatic conditions of The Gambia and can effectively utilize the country's abundant solar energy resources for sustainable mango preservation.

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