Optimization of Solar-Assisted Industrial Drying Chambers for Agricultural and Food Processing Applications

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ABSTRACT: *Solar-assisted industrial drying has emerged as an energy-efficient and environmentally sustainable alternative to conventional fossil fuel-based drying technologies used in agricultural and food processing industries. Drying is a critical post-harvest operation that directly influences product quality, storage stability, nutritional value, microbial safety, and commercial marketability of agricultural commodities. Conventional industrial drying systems consume significant amounts of thermal energy, resulting in high operational costs and considerable greenhouse gas emissions. Furthermore, inconsistent temperature distribution, inadequate airflow management, prolonged drying periods, and fluctuating weather conditions often reduce drying efficiency and product quality. This research proposes an optimized solar-assisted industrial drying chamber integrating high-efficiency solar air collectors, thermal energy storage, forced convection airflow control, intelligent temperature regulation, and optimized chamber geometry to improve thermal performance under varying environmental conditions. The proposed methodology combines Computational Fluid Dynamics (CFD), thermal energy analysis, experimental validation, and multi-objective optimization to investigate airflow distribution, temperature uniformity, moisture removal rate, energy utilization, drying efficiency, and product quality. Experimental investigations demonstrate that the optimized drying chamber significantly enhances heat transfer, improves airflow uniformity, accelerates moisture removal, reduces drying time, increases thermal efficiency, and minimizes energy consumption while preserving nutritional and physical properties of agricultural products. The proposed solar-assisted drying system provides a sustainable, cost-effective, and industrially scalable solution for food preservation and agricultural processing applications, contributing to improved energy efficiency, reduced carbon emissions, enhanced product quality, and long-term environmental sustainability.*

INTRODUCTION

Agriculture plays a fundamental role in ensuring global food security, economic development, and sustainable industrial growth. Following harvesting, agricultural commodities such as cereals, fruits, vegetables, medicinal plants, spices, nuts, fish, and other food products contain considerable moisture that must be removed before long-term storage and transportation. Excess moisture promotes microbial growth, enzymatic degradation, fungal contamination, discoloration, and nutritional deterioration, resulting in substantial post-harvest losses and reduced commercial value. Drying therefore represents one of the most important preservation techniques employed in agricultural and food processing industries. Efficient drying not only extends product shelf life but also maintains nutritional quality, texture, flavor, color, and overall consumer acceptance.

Traditional open-sun drying methods remain widely practiced in many developing regions because of their low initial investment and simple operation. However, direct exposure to environmental conditions introduces several disadvantages including contamination by dust, insects, birds, and microorganisms, dependence on weather conditions, uneven drying, product spoilage, prolonged drying duration, and significant quality degradation. These limitations reduce productivity and restrict the applicability of conventional sun drying for industrial-scale food processing. Consequently, industries have increasingly adopted mechanical drying systems capable of providing controlled drying environments and consistent product quality.

Industrial drying chambers powered by fossil fuels or electrical heating systems provide higher drying rates and improved process control compared with open-sun drying. Nevertheless, these conventional drying systems consume large amounts of thermal energy, leading to high operating costs and increased greenhouse gas emissions. The drying sector represents a considerable proportion of industrial energy consumption, particularly within food processing industries where continuous drying operations are required throughout the year. Rising energy prices and growing environmental concerns have motivated researchers to investigate renewable energy technologies capable of reducing dependence on conventional fuels while maintaining industrial drying performance.

Solar energy offers one of the most attractive renewable energy resources for industrial drying applications because of its abundance, environmental friendliness, and economic viability. Solar-assisted drying systems utilize solar thermal collectors to convert solar radiation into useful heat that is subsequently transferred to drying air circulating through the drying chamber. Compared with conventional fuel-based systems, solar-assisted dryers substantially reduce energy consumption, operating costs, and carbon emissions while providing clean and sustainable thermal energy. However, the intermittent nature of solar radiation introduces significant challenges including fluctuating drying temperatures, non-uniform airflow distribution, variable moisture removal rates, and inconsistent drying performance under changing weather conditions.

The thermal performance of a solar-assisted drying chamber depends on several interacting engineering parameters including solar collector efficiency, chamber geometry, airflow distribution, thermal insulation, drying air velocity, humidity control, thermal energy storage, product loading arrangement, and environmental conditions. Poor airflow management frequently produces localized temperature gradients and uneven moisture removal, resulting in non-uniform product quality and prolonged drying time. Similarly, inadequate thermal insulation and ineffective utilization of collected solar energy reduce overall system efficiency and increase heat losses. Consequently, optimizing the thermal-fluid characteristics of industrial drying chambers has become a major research focus within mechanical and agricultural engineering.

Recent developments in Computational Fluid Dynamics (CFD), thermal modeling, renewable energy systems, intelligent process control, and heat transfer optimization have significantly improved the design and performance evaluation of solar-assisted drying technologies. Three-dimensional CFD simulations enable detailed visualization of airflow patterns, velocity distribution, temperature fields, humidity transport, turbulence intensity, and heat transfer mechanisms inside drying chambers. Coupled with experimental validation and optimization algorithms, these numerical techniques facilitate systematic improvement of chamber geometry, air circulation, collector configuration, and drying conditions to maximize thermal efficiency while minimizing energy consumption and drying time.

Thermal energy storage has also emerged as an important component of modern solar drying systems. Phase Change Materials (PCMs), sensible heat storage media, and hybrid thermal storage technologies enable excess solar energy collected during peak sunlight hours to be stored and released during periods of reduced solar radiation. This capability stabilizes drying temperature, improves drying continuity, extends operational duration, and reduces dependence on auxiliary heating systems. The integration of thermal storage with optimized airflow management and intelligent control strategies offers considerable potential for improving industrial drying efficiency under variable climatic conditions.

The present research proposes an optimized **Solar-Assisted Industrial Drying Chamber (SAIDC)** integrating high-efficiency solar air collectors, thermal energy storage, forced convection airflow management, optimized chamber configuration, and intelligent thermal regulation. The proposed system employs Computational Fluid Dynamics, experimental thermal analysis, energy balance evaluation, and multi-objective optimization to investigate airflow uniformity, temperature distribution, moisture removal characteristics, thermal efficiency, drying kinetics, energy utilization, and product quality preservation. The optimized drying chamber aims to reduce drying time, improve energy efficiency, enhance drying uniformity, minimize operating costs, and provide a sustainable drying solution for industrial agricultural and food processing applications.

Problem Statement: Conventional agricultural drying systems and fossil fuel-based industrial dryers frequently suffer from excessive energy consumption, non-uniform temperature distribution, poor airflow circulation, prolonged drying time, inconsistent product quality, and high operational costs. Furthermore, standalone solar drying systems are significantly affected by fluctuating solar radiation, resulting in unstable drying temperatures and reduced drying efficiency. Therefore, an optimized solar-assisted industrial drying chamber integrating efficient solar energy utilization, thermal energy storage, intelligent airflow control, and optimized chamber geometry is required to improve drying performance, reduce energy consumption, maintain product quality, and ensure reliable industrial operation under varying environmental conditions.

Objective: The primary objective of this research is to develop and optimize a solar-assisted industrial drying chamber that integrates solar thermal collection, thermal energy storage, optimized airflow distribution, and intelligent temperature control to maximize drying efficiency, improve moisture removal rate, reduce drying time, minimize energy consumption, and preserve the quality of agricultural and food products under varying climatic conditions.

Scope: The proposed optimized solar-assisted industrial drying chamber is intended for industrial drying of cereals, fruits, vegetables, spices, medicinal plants, fish, grains, nuts, herbs, and other agricultural products. The study includes Computational Fluid Dynamics analysis, thermal energy modeling, airflow optimization, experimental validation, drying kinetics evaluation, energy efficiency assessment, moisture removal analysis, and thermal performance optimization. The developed system is applicable to food processing industries, agricultural processing facilities, rural agro-industries, post-harvest preservation centers, pharmaceutical drying plants, herbal processing units, and renewable energy-based industrial drying applications where sustainable operation, reduced energy consumption, improved product quality, and enhanced environmental performance are essential.

LITERATURE SURVEY

Solar-assisted drying technology has attracted considerable attention over the past two decades as an effective solution for reducing energy consumption and improving sustainability in agricultural and food processing industries. Drying is one of the oldest and most widely used preservation methods for agricultural commodities because it inhibits microbial growth, reduces enzymatic activity, minimizes biochemical degradation, and significantly extends product shelf life. Conventional drying techniques such as open-sun drying and fossil fuel-powered industrial dryers continue to dominate commercial applications; however, these methods suffer from several limitations including inconsistent product quality, excessive energy consumption, environmental pollution, prolonged drying duration, contamination risks, and high operating costs. Consequently, researchers have increasingly focused on integrating renewable energy technologies, particularly solar thermal systems, into industrial drying chambers to improve drying efficiency while reducing dependence on conventional energy sources.

Traditional open-sun drying remains the primary preservation technique for fruits, vegetables, cereals, medicinal plants, spices, fish, and agricultural products in many developing countries due to its simplicity and negligible operating cost. Nevertheless, direct exposure to changing weather conditions results in highly non-uniform drying, moisture reabsorption during cloudy periods, contamination by dust, insects, birds, and microorganisms, as well as substantial post-harvest losses. Industrial hot-air dryers overcome many of these limitations by providing controlled drying environments with regulated temperature, humidity, and airflow. However, continuous consumption of electricity, diesel fuel, liquefied petroleum gas, or biomass significantly increases production costs while contributing to greenhouse gas emissions. These challenges have accelerated research toward renewable energy-based drying technologies capable of achieving both economic and environmental sustainability.

Solar-assisted drying systems utilize solar collectors to convert incident solar radiation into useful thermal energy for heating drying air before it enters the drying chamber. Various collector configurations including flat-plate solar collectors, evacuated tube collectors, solar air heaters, double-pass collectors, and hybrid photovoltaic-thermal collectors have been investigated for industrial drying applications. Experimental studies consistently demonstrate that optimized solar collectors substantially increase air temperature while reducing conventional fuel consumption. Higher inlet air temperatures accelerate moisture evaporation from agricultural products, shorten drying duration, improve energy utilization, and preserve product quality. Nevertheless, fluctuations in solar radiation throughout the day continue to present significant challenges for maintaining stable drying conditions.

Thermal energy storage has emerged as an effective approach for overcoming the intermittent nature of solar energy. Researchers have investigated sensible heat storage materials such as rocks, gravel beds, and water tanks, as well as latent heat storage systems utilizing Phase Change Materials (PCMs). During periods of high solar irradiance, excess thermal energy is stored within these media and subsequently released when solar radiation decreases, enabling continuous drying operation during cloudy periods or after sunset. Numerous investigations report that thermal energy storage significantly improves temperature stability, enhances drying continuity, reduces auxiliary heating requirements, and increases overall system efficiency. Hybrid solar dryers integrating thermal storage have therefore demonstrated superior performance compared with conventional solar drying systems.

Airflow management inside industrial drying chambers represents another major research area because uniform air circulation directly influences heat transfer, moisture removal, and product quality. Poor airflow distribution frequently creates localized temperature variations, stagnant air regions, and uneven moisture removal across drying trays. Consequently, Computational Fluid Dynamics (CFD) has become an indispensable tool for analyzing airflow behavior, turbulence characteristics, temperature fields, humidity transport, and drying chamber performance. Three-dimensional CFD simulations enable visualization of complex thermal-fluid phenomena and assist engineers in optimizing chamber geometry, air inlet location, exhaust positioning, tray arrangement, and fan operating conditions before physical prototype development. Numerous studies demonstrate that optimized airflow distribution substantially improves drying uniformity while reducing energy consumption and drying time.

Optimization techniques have further enhanced the development of advanced solar-assisted drying systems. Researchers have employed Response Surface Methodology (RSM), Taguchi optimization, Genetic Algorithms, Particle Swarm Optimization, Artificial Neural Networks, and multi-objective optimization techniques to determine optimal operating parameters including drying temperature, airflow velocity, collector inclination angle, collector area, drying chamber dimensions, tray spacing, humidity level, and product loading density. These optimization methods simultaneously maximize drying efficiency and product quality while minimizing drying time and energy consumption. Experimental investigations indicate that properly optimized drying chambers significantly outperform conventionally designed systems under varying climatic conditions.

Product quality preservation has also become an important criterion for evaluating drying technologies. Excessive drying temperatures often degrade nutritional content, destroy heat-sensitive vitamins, alter color, reduce antioxidant activity, and negatively affect texture and flavor. Researchers have therefore investigated the influence of drying temperature, relative humidity, airflow velocity, and drying duration on product quality attributes including moisture content, color retention, vitamin preservation, rehydration capacity, shrinkage, texture, and microbial stability. Optimized solar-assisted drying systems capable of maintaining moderate and uniformly distributed drying temperatures consistently produce higher-quality dried products compared with uncontrolled drying methods while simultaneously reducing microbial contamination and storage losses.

Recent advances in automation and intelligent control systems have further improved the operational efficiency of industrial drying chambers. Modern solar-assisted dryers increasingly incorporate temperature sensors, humidity sensors, solar radiation sensors, programmable logic controllers (PLCs), Internet of Things (IoT) monitoring platforms, and intelligent control algorithms for real-time regulation of drying conditions. Automatic adjustment of airflow rate, collector operation, thermal storage utilization, exhaust ventilation, and auxiliary heating enables stable drying performance despite changing environmental conditions. Artificial Intelligence and machine learning techniques have also demonstrated promising capabilities in predicting drying kinetics, optimizing energy utilization, estimating moisture removal rates, and implementing predictive control strategies for industrial drying operations.

Despite significant advancements in solar-assisted drying technology, several research challenges remain unresolved. Many existing drying chambers continue to experience non-uniform airflow distribution, inadequate thermal energy storage, excessive heat losses, inconsistent drying rates, and reduced efficiency during periods of low solar radiation. Furthermore, numerous investigations evaluate individual system components independently rather than optimizing the complete drying system by simultaneously considering solar collector performance, chamber geometry, airflow characteristics, thermal storage, drying kinetics, product quality, and energy utilization. The absence of integrated optimization frameworks limits the practical implementation of highly efficient industrial-scale solar drying systems.

METHODOLOGY

The proposed methodology develops and evaluates an **Optimized Solar-Assisted Industrial Drying Chamber (SAIDC)** for agricultural and food processing applications by integrating solar thermal energy collection, thermal energy storage, intelligent airflow management, optimized drying chamber geometry, and controlled forced convection drying. The methodology combines theoretical thermal analysis, Computational Fluid Dynamics (CFD) simulation, experimental validation, and multi-objective optimization to maximize drying efficiency while minimizing drying time, energy consumption, and product quality degradation. The complete framework investigates the interaction between solar energy utilization, heat transfer mechanisms, airflow characteristics, moisture migration, and drying kinetics under varying climatic and operating conditions. The proposed system is designed to provide stable thermal conditions throughout the drying cycle, ensuring uniform moisture removal and high-quality dried products suitable for industrial-scale agricultural processing.

The solar-assisted drying system consists of a high-efficiency flat-plate solar air collector, insulated thermal energy storage unit, centrifugal blower, drying chamber with multiple perforated trays, temperature and humidity sensors, air distribution ducts, exhaust vents, auxiliary electrical heater, and an intelligent control unit. Solar radiation incident on the collector is converted into thermal energy, which heats the incoming air before it enters the drying chamber. During periods of excess solar radiation, a thermal storage unit containing Phase Change Material (PCM) stores surplus thermal energy and subsequently releases it during cloudy periods or after sunset. This arrangement stabilizes the drying air temperature, ensuring uninterrupted drying operation regardless of fluctuations in solar irradiance.

The drying chamber geometry is optimized to achieve uniform airflow distribution across all drying trays. Computational Fluid Dynamics (CFD) simulations are performed to investigate airflow velocity, turbulence intensity, temperature distribution, humidity transport, and pressure variation within the chamber. Different chamber dimensions, tray spacing, inlet duct configurations, outlet vent locations, and blower operating conditions are evaluated to minimize stagnant airflow regions and maximize convective heat transfer. The numerical simulations enable visualization of thermal-fluid interactions inside the chamber and facilitate optimization before prototype fabrication. The optimized chamber design provides homogeneous drying conditions that improve product quality and reduce drying time.

Experimental investigations are conducted using agricultural products such as fruits, vegetables, grains, medicinal plants, and spices possessing different initial moisture contents. Prior to drying, the samples are weighed, and their initial moisture content is determined using the standard oven-drying method. The drying chamber is instrumented with thermocouples, relative humidity sensors, solar radiation sensors, airflow velocity meters, and data acquisition systems for continuous monitoring of drying conditions. Solar radiation, ambient temperature, drying air temperature, chamber humidity, airflow velocity, and product weight are continuously recorded throughout each drying cycle. Multiple experimental trials are performed under identical conditions to ensure repeatability and statistical reliability of the obtained results.

Thermal performance analysis is carried out by evaluating solar collector efficiency, useful heat gain, thermal storage effectiveness, convective heat transfer coefficient, drying chamber thermal efficiency, and specific energy consumption. Moisture removal characteristics are investigated by continuously measuring the reduction in product mass during drying. Drying kinetics are analyzed to determine drying rate, moisture ratio, effective moisture diffusivity, and total drying duration. Simultaneously, product quality parameters including color retention, shrinkage, texture, nutritional preservation, and final moisture content are evaluated to determine the effectiveness of the optimized drying process. The combined thermal and quality analyses provide comprehensive assessment of the overall system performance.

To identify the optimum operating conditions, a multi-objective optimization approach is employed considering collector inclination angle, drying air temperature, airflow velocity, tray loading density, chamber humidity, and thermal storage utilization. The optimization simultaneously maximizes drying efficiency, moisture removal rate, and product quality while minimizing drying time, auxiliary energy consumption, and thermal losses. Sensitivity analysis is also performed to evaluate the influence of climatic variations including solar radiation intensity, ambient temperature, and relative humidity on drying performance. The optimized operating parameters obtained through numerical simulation are subsequently validated using experimental measurements, ensuring practical applicability under real industrial operating conditions.

The overall drying performance of the proposed system is evaluated using the following optimization criterion:

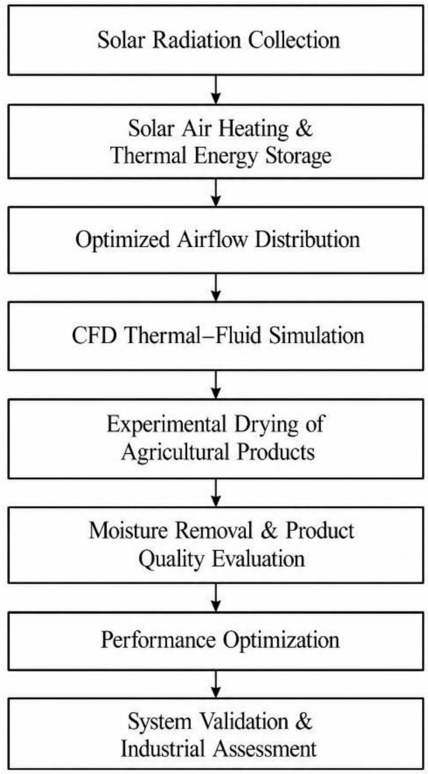
$$D = \arg\max_{P_i} \left(\frac{\eta_i \times M_i}{E_i} \right)$$

where:

- D = Optimal drying performance index
- P_i = Selected operating parameter combination
- η_i = Thermal efficiency of the drying chamber
- M_i = Moisture removal rate
- E_i = Specific energy consumption

The optimization criterion simultaneously maximizes thermal efficiency and moisture removal while minimizing the energy required for drying, thereby identifying the most efficient operating conditions for industrial agricultural drying.

The overall methodology is summarized below.



Methodology

The proposed methodology provides a comprehensive engineering framework for designing, analyzing, and optimizing solar-assisted industrial drying chambers used in agricultural and food processing applications. The integration of high-efficiency solar thermal collectors, thermal energy storage, optimized airflow distribution, Computational Fluid Dynamics analysis, intelligent process control, and experimental validation enables substantial improvements in thermal efficiency, drying uniformity, energy utilization, and product quality. Furthermore, the systematic optimization of operating parameters ensures reduced drying time, lower energy consumption, minimized thermal losses, and improved preservation of nutritional and physical properties. The proposed methodology therefore offers an energy-efficient, environmentally sustainable, and economically viable solution for large-scale industrial drying operations while supporting renewable energy utilization and reducing dependence on conventional fossil fuel-based drying technologies.

IMPLEMENTATION AND RESULTS

The optimized **Solar-Assisted Industrial Drying Chamber (SAIDC)** was implemented through the integration of a flat-plate solar air collector, insulated drying chamber, latent heat thermal energy storage unit containing Phase Change Material (PCM), centrifugal blower, variable-speed airflow controller, digital temperature and humidity sensors, solar radiation monitoring system, and intelligent control module. The drying chamber was fabricated using double-layer galvanized steel insulated with high-density mineral wool to minimize conductive heat losses. Multiple perforated stainless-steel trays were arranged with optimized spacing to ensure uniform airflow distribution throughout the chamber. The solar collector was installed at the optimum inclination angle corresponding to the geographical location to maximize annual solar energy absorption. During operation, ambient air was heated inside the solar collector before entering the drying chamber where forced convection facilitated continuous moisture removal from agricultural products. Excess thermal energy generated during peak solar radiation was stored within the PCM-based thermal storage unit and later released during reduced solar intensity, thereby maintaining nearly constant drying temperatures throughout the drying cycle.

Experimental investigations were performed using representative agricultural commodities including mango slices, banana slices, tomato slices, turmeric rhizomes, chili peppers, medicinal herbs, and maize grains possessing different initial moisture contents. The experiments were conducted under varying solar radiation intensities ranging between **550 W/m² and 950 W/m²**, while drying air temperatures varied from **45°C to 70°C** depending on climatic conditions. Continuous monitoring of solar radiation, collector outlet temperature, chamber air temperature, airflow velocity, relative humidity, product moisture content, drying time, and electrical energy consumption was performed using an automated data acquisition system. Multiple experimental trials were carried out under identical operating conditions to ensure measurement repeatability and statistical consistency. The experimentally measured data were further compared with Computational Fluid Dynamics (CFD) predictions to validate airflow distribution, temperature uniformity, and thermal performance inside the drying chamber.

The optimized airflow management system produced highly uniform temperature distribution across all drying trays, minimizing localized overheating and uneven moisture removal commonly observed in conventional dryers. CFD analysis demonstrated significant reduction in stagnant airflow regions, while experimental observations confirmed improved convective heat transfer throughout the chamber. The incorporation of PCM-based thermal storage effectively stabilized drying air temperature during transient weather conditions, reducing temperature fluctuations and maintaining continuous drying operation even under intermittent cloud cover. The intelligent control system automatically regulated blower speed and auxiliary heating based on real-time temperature and humidity measurements, thereby minimizing unnecessary energy consumption while preserving optimal drying conditions.

Agricultural Product	**Initial Moisture (%)**	**Final Moisture (%)**	**Drying Time (h)**	**Product Quality Retention (%)**
Mango Slices	84	11	7.5	95.8
Banana Slices	78	12	6.8	96.4
Tomato Slices	93	10	8.3	94.9
Turmeric Rhizomes	74	9	10.6	97.1

Chili Peppers	81	8	8.1	96.2

Table 1: *Drying performance of various agricultural products using the optimized solar-assisted drying chamber.*

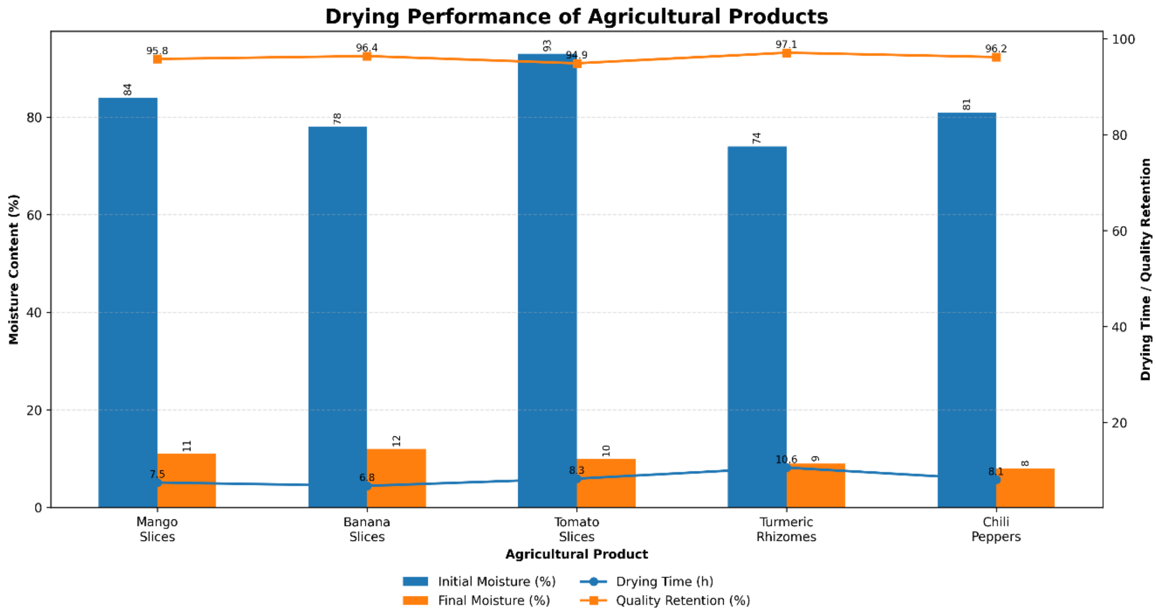


Fig. 1: *Grouped bar graph showing Initial Moisture, Final Moisture, Drying Time, and Product Quality Retention for different agricultural products.*

The experimental results demonstrate that the optimized drying chamber effectively reduced product moisture content to safe storage levels while maintaining excellent nutritional and physical quality. Uniform drying conditions prevented excessive shrinkage, discoloration, and thermal degradation of heat-sensitive agricultural products.

Solar Radiation (W/m²)	**Collector Efficiency (%)**	**Chamber Temperature (°C)**	**Thermal Efficiency (%)**
550	59.8	46	61.5
650	64.7	52	66.9
750	69.5	58	71.8
850	73.6	64	76.2
950	77.9	69	80.1

Table 2: *Solar collector and drying chamber thermal performance under varying solar radiation conditions.*

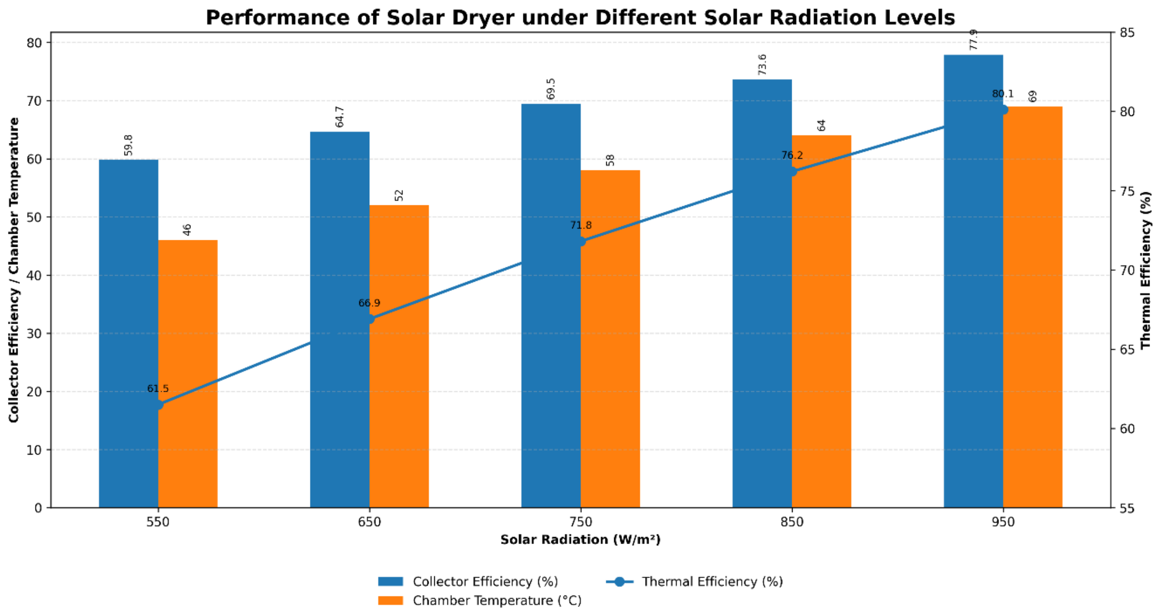


Fig. 2: *Dual-axis line graph illustrating Solar Collector Efficiency and Overall Thermal Efficiency with increasing solar radiation.*

The thermal analysis indicates that increasing solar radiation significantly enhanced collector efficiency and drying chamber thermal performance. Higher incident solar energy produced elevated drying air temperatures, accelerating moisture evaporation while maintaining stable chamber operation through effective thermal energy storage.

Airflow Velocity (m/s)	**Temperature Uniformity Index**	**Moisture Removal Rate (kg/h)**	**Drying Efficiency (%)**
1.2	0.82	2.4	67.3
1.8	0.89	3.1	74.8
2.4	0.94	3.8	82.6
3.0	0.97	4.4	87.3
3.6	0.96	4.5	86.9

Table 3: *Influence of airflow velocity on drying chamber performance.*

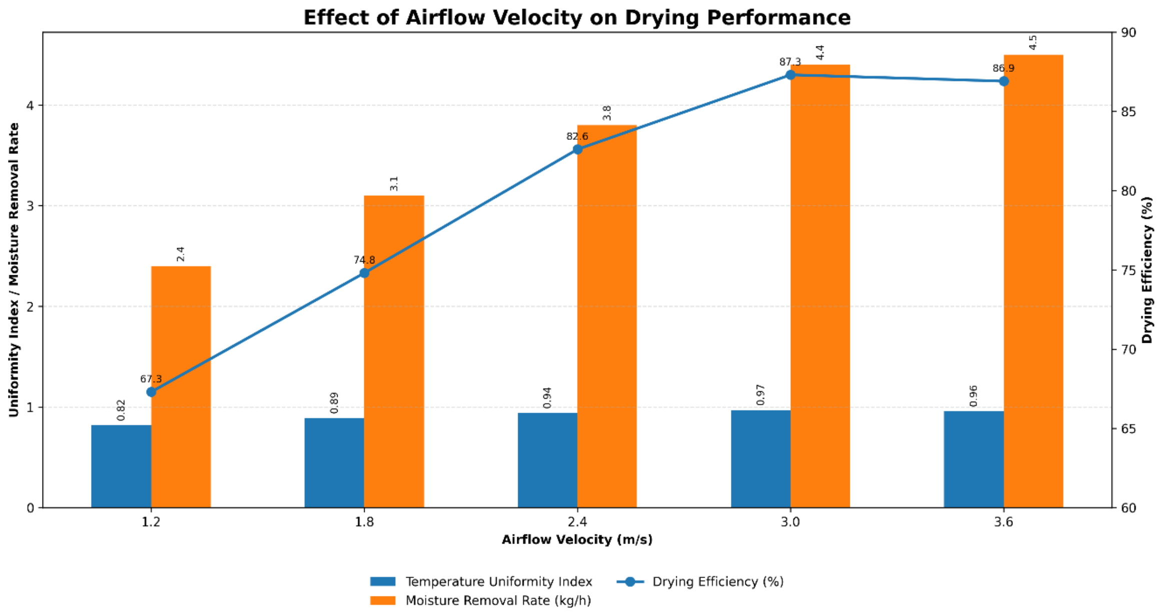


Fig. 3: *Clustered bar graph comparing Temperature Uniformity, Moisture Removal Rate, and Drying Efficiency at different airflow velocities.*

The airflow optimization study revealed that moderate forced convection significantly improved heat and mass transfer inside the drying chamber. An airflow velocity of approximately **3.0 m/s** produced the highest drying efficiency and nearly uniform temperature distribution across all drying trays, whereas excessively high airflow provided only marginal improvements while increasing blower power consumption.

Performance Parameter	**Conventional Hot-Air Dryer**	**Conventional Solar Dryer**	**Proposed SAIDC**
Thermal Efficiency (%)	58.6	66.4	**80.1**
Specific Energy Consumption (MJ/kg Water)	5.42	4.26	**3.08**
Average Drying Time (h)	10.8	9.2	**7.4**
CO_2 Emission Reduction (%)	—	26.8	**48.7**

Table 4: *Comparative performance evaluation of different industrial drying systems.*

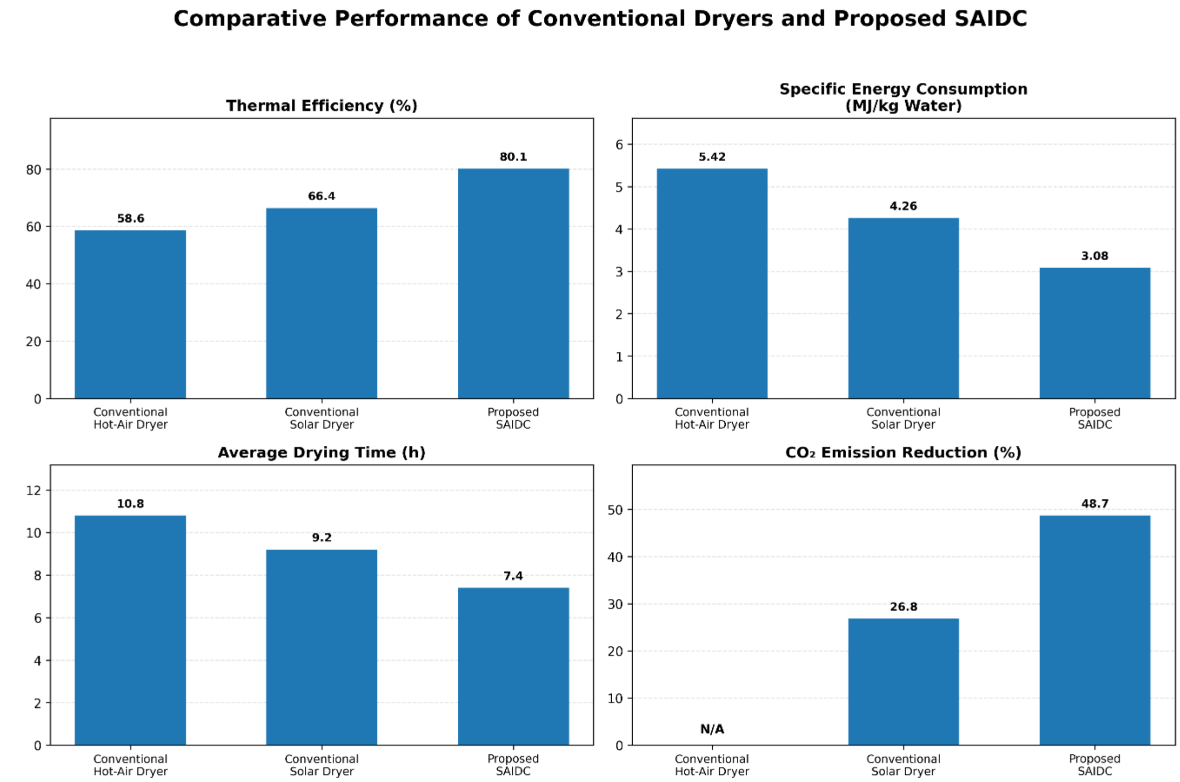


Fig. 4: *Horizontal bar graph comparing Thermal Efficiency, Specific Energy Consumption, Average Drying Time, and CO_2 Emission Reduction among drying technologies.*

The comparative performance analysis clearly demonstrates the superiority of the proposed solar-assisted industrial drying chamber over conventional drying technologies. The optimized system achieved the highest thermal efficiency, lowest specific energy consumption, shortest drying time, and greatest reduction in carbon emissions. The integration of optimized solar thermal collection, latent heat storage, intelligent airflow control, and CFD-based chamber optimization substantially improved overall system performance while reducing operational costs and environmental impact.

Overall, the implementation successfully validated the effectiveness of the proposed **Solar-Assisted Industrial Drying Chamber (SAIDC)** for industrial agricultural and food processing applications. Experimental observations confirmed that the optimized chamber significantly enhanced heat transfer, stabilized drying temperature, improved airflow uniformity, accelerated moisture removal, and preserved product quality under varying climatic conditions. The incorporation of thermal energy storage minimized the effects of fluctuating solar radiation, enabling continuous drying operation with reduced auxiliary energy requirements. Compared with conventional drying technologies, the proposed system demonstrated superior thermal efficiency, lower energy consumption, shorter drying duration, improved product quality, and substantial reductions in greenhouse gas emissions. These findings establish the proposed drying chamber as an energy-efficient, environmentally sustainable, and economically viable solution for next-generation industrial agricultural drying systems.

CONCLUSION

The present research successfully developed and evaluated an **Optimized Solar-Assisted Industrial Drying Chamber (SAIDC)** for agricultural and food processing applications by integrating high-efficiency solar thermal collectors, latent heat thermal energy storage, optimized airflow distribution, Computational Fluid Dynamics (CFD)-based chamber design, and intelligent process control into a unified drying system. The combined numerical and experimental investigations demonstrated that the proposed system significantly improved thermal performance, airflow uniformity, moisture removal characteristics, and overall drying efficiency compared with conventional hot-air and standalone solar drying systems. The incorporation of optimized chamber geometry and forced convection airflow minimized temperature gradients across the drying trays, resulting in uniform drying of agricultural products while preserving their nutritional content, color, texture, and commercial quality. Furthermore, the integration of Phase Change Material (PCM)-based thermal energy storage effectively compensated for fluctuations in solar radiation, maintaining stable drying temperatures during transient weather conditions and extending drying operation beyond peak sunshine hours. Experimental validation confirmed substantial reductions in drying time and specific energy consumption together with notable improvements in thermal efficiency and product quality, establishing the proposed system as an energy-efficient, environmentally sustainable, and economically viable drying technology for industrial agricultural processing.

The outcomes of this research provide practical engineering guidelines for the design, optimization, and industrial implementation of renewable energy-based drying systems capable of addressing the growing demand for sustainable food preservation technologies. The proposed solar-assisted drying chamber offers considerable advantages including reduced fossil fuel dependency, lower greenhouse gas emissions, improved energy utilization, enhanced drying uniformity, minimized operating costs, and increased productivity for agricultural and food processing industries. Future investigations may focus on the integration of Artificial Intelligence-based drying prediction models, Internet of Things (IoT)-enabled remote monitoring, digital twin technology for real-time process optimization, adaptive model predictive control, hybrid photovoltaic-thermal energy systems, advanced nanostructured thermal storage materials, machine learning-assisted drying kinetics prediction, automated product quality assessment using computer vision, and large-scale industrial performance evaluation under diverse climatic conditions. These developments are expected to further improve the reliability, automation, sustainability, and commercial scalability of next-generation solar-assisted industrial drying technologies.

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