



Design and Development of A Smart AI-Integrated Solar Drying System

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Abstract

This paper presents the design and development of a simple AI-enhanced solar dryer through the integration of Machine Learning (ML) techniques into the drying process of food and bio-based materials. Traditional drying systems often rely on conventional physics-based models, which may have limitations in accurately predicting drying behavior under varying environmental conditions. By incorporating AI and data-driven machine learning approaches, the proposed system improves prediction accuracy, enhances process efficiency, and enables intelligent real-time monitoring and control. The study explores the application of machine learning models for analyzing key drying parameters such as temperature, humidity, airflow, and moisture content, allowing for adaptive and optimized drying performance. Techniques such as nonlinear control and multi-objective optimization are employed to improve energy utilization, reduce drying time, and maintain product quality. The integration of sensor technologies with AI software tools further strengthens the system's ability to respond dynamically to environmental changes and operational demands. In addition, this research highlights the potential of developing open-source datasets and smart analytical frameworks to support the continuous improvement of machine learning algorithms for solar drying applications. The convergence of artificial intelligence, sensor-based monitoring, process analysis, and software engineering provides a promising pathway toward the development of intelligent, cost-effective, and sustainable solar drying systems suitable for industrial and agricultural applications.

Keywords: Machine Learning (ML), Artificial Intelligence (AI), Solar Dryer, Smart Drying System, Process Optimization.

Introduction

The drying process of food and biomaterials is a complex operation involving simultaneous heat and mass transfer mechanisms, making accurate modeling and process optimization challenging when using conventional physics-based approaches. Traditional drying models often struggle to capture the nonlinear behavior, environmental variability, and dynamic interactions that occur during the drying process, which can limit prediction accuracy and reduce the effectiveness of real-time process control. Recent advances in Artificial Intelligence (AI) and Machine Learning (ML) provide promising alternatives by enabling the development of data-driven models capable of learning complex patterns and adapting to varying operational conditions. The integration of ML techniques into solar drying systems offers significant potential for improving drying efficiency, product quality, and energy utilization. By applying machine learning methods such as predictive modeling, nonlinear control, and multi-objective optimization, it becomes possible to accurately monitor and regulate critical drying parameters, including temperature, humidity, airflow, and moisture content. These intelligent systems can make real-time adjustments based on sensor data, thereby

enhancing system performance and minimizing drying time while preserving the nutritional and physical properties of dried products.

Solar drying is widely recognized as an environmentally friendly and cost-effective method for preserving agricultural products and biomaterials through the use of renewable solar energy. However, conventional solar dryers often face challenges related to inconsistent weather conditions, limited process control, and uneven drying performance. The incorporation of AI-driven monitoring and control systems into solar dryers addresses these limitations by enabling adaptive decision-making and automated optimization of drying conditions. Furthermore, the convergence of AI software tools, sensor technologies, and process analysis creates opportunities for the development of intelligent solar drying systems tailored for both small-scale and industrial applications. Future advancements in this field may include the creation of open-source datasets for training robust machine learning algorithms, enhanced sensor integration for precise environmental monitoring, and the implementation of smart control strategies capable of autonomous system management. This study focuses on the design and development of a simple AI-enhanced solar dryer, highlighting the advantages of integrating machine learning into solar drying processes. The research aims to demonstrate how intelligent drying systems can improve operational efficiency, product quality, and sustainability, while contributing to the advancement of smart agricultural and industrial drying technologies.

Different Methods of Solar Drying

Solar drying can be carried out using several methods, each designed to suit specific materials, environmental conditions, and operational requirements. The major methods of solar drying include direct solar drying, indirect solar drying, mixed-mode solar drying, and hybrid solar drying systems.

Direct Solar Drying

In direct solar drying, the material to be dried is exposed directly to solar radiation within an enclosed drying chamber. The sunlight passes through a transparent cover, heating both the product and the surrounding air. This method is simple, economical, and suitable for small-scale applications, though it may result in uneven drying and possible degradation of sensitive products due to direct exposure to sunlight.

Indirect Solar Drying

Indirect solar drying involves the use of a separate solar collector to heat air, which is then circulated through the drying chamber containing the material. Since the product is not directly exposed to sunlight, this method offers better protection against contamination and helps preserve the quality, color, and nutritional value of the dried material.

Mixed-Mode Solar Drying

Mixed-mode solar drying combines the features of both direct and indirect drying. The drying chamber receives heat from both direct solar radiation and pre-heated air from a solar collector. This approach improves drying efficiency and reduces drying time compared to single-mode systems.

Problem Statement

The development of solar drying systems faces several challenges, including inefficient energy utilization, inconsistent product quality, and limited adaptability to environmental conditions. Current solar drying methods often rely on manual adjustments and lack real-time monitoring, leading to suboptimal performance and potential product degradation¹¹. The integration of Artificial Intelligence (AI) offers a promising solution by enabling advanced control strategies, real-time monitoring, and predictive maintenance². However, existing AI-assisted solar drying systems require further optimization to fully leverage AI capabilities. The primary objective of this research is to develop and optimize an AI-assisted solar dryer system that enhances performance, improves energy efficiency, and ensures consistent product quality. This involves addressing key challenges such as developing AI models to accurately predict and optimize critical parameters like temperature, humidity, and airflow within the solar dryer, implementing adaptive control algorithms to dynamically adjust drying parameters in response to environmental changes,

integrating AI-enabled monitoring systems for real-time insights and anomaly detection, and developing comprehensive modelling approaches that combine AI with computational fluid dynamics and product quality analysis³. By addressing these challenges, this research aims to create an optimized AI-assisted solar dryer system that significantly improves upon existing technologies, contributing to sustainable agricultural practices and enhanced food security¹³.

Key Processes in Conventional Dryer

In a conventional solar dryer, several key processes occur to facilitate the efficient drying of agricultural products. The primary process begins with solar radiation absorption, where solar collectors or transparent covers allow sunlight to enter the drying chamber, heating the air and surfaces inside¹. This absorbed radiation is then transferred to the surrounding air through heat transfer, increasing the air's temperature, which is crucial for moisture removal. As the air inside the dryer is heated, convective heat transfer takes place, where hot air rises due to its lower density, creating natural convection currents that distribute heat evenly and facilitate moisture removal from the product and shown in Fig.2. As the heated air circulates around the product, moisture evaporation occurs, driven by the temperature difference between the product surface and the surrounding air. This process moves moisture from areas of higher concentration (the product surface) to areas of lower concentration (the air). To maintain optimal drying conditions, humidity control is essential. Proper ventilation or airflow control mechanisms are used to remove humid air from the drying chamber and replace it with drier air from outside, preventing moisture reabsorption into the product⁹.

Once the drying process is complete, product cooling is necessary to prevent overheating and maintain product quality. In conventional solar dryers, cooling occurs naturally as the dryer's temperature decreases after sunset or when solar radiation diminishes. Alternatively, some dryers may use fans or ventilation systems to expedite cooling. Throughout the drying process, moisture removal is continuous, with moisture being expelled from the drying chamber into the surrounding environment. This is essential for reducing the moisture content of the product to the desired level, ensuring proper preservation and storage. Conventional solar dryers as shown in Fig.1, despite their eco-friendly and cost-effective nature, face several limitations that impact their effectiveness and efficiency. One of the primary constraints is their dependency on weather conditions, as they rely heavily on solar radiation, making them susceptible to variations in cloud cover, rain, and seasonal changes. This can significantly reduce drying rates and prolong drying times. Additionally, conventional solar dryers often have a limited drying capacity, with small-scale models struggling to efficiently dry large quantities of produce, leading to extended drying times or insufficient capacity for commercial use.

Another issue is inconsistent drying rates due to uneven airflow distribution and temperature gradients within the drying chamber, which can result in uneven drying and affect product quality. These dryers typically lack precise control over drying parameters such as temperature, airflow, and humidity, making it challenging to maintain optimal conditions for different products. Furthermore, conventional solar dryers are limited to operating only during daylight hours, restricting their operational flexibility compared to other drying methods. Seasonal variability in solar radiation also affects their performance, causing fluctuations in drying times and product quality. Lastly, while solar energy is free, the initial investment for constructing and installing these dryers can be high, deterring small-scale farmers or those with limited financial resources.

AI Assisted Solar Dryer

The AI Solar Dryer embodies a revolutionary technology that seamlessly integrates Artificial Intelligence (AI) with solar drying systems. This innovative approach is designed to optimize performance, enhance efficiency, and significantly improve product quality⁶. By leveraging the power of AI algorithms, these advanced dryers can predict and control critical parameters such as temperature, humidity, and airflow with greater precision. This capability enables a more efficient drying process, allowing for real-time adjustments that adapt to changing environmental conditions⁷. The integration of AI in solar drying systems represents a significant leap forward, offering a dynamic and adaptive approach to address the complex interactions involved in the drying process. This technology not only maximizes energy efficiency but also ensures consistent product quality, making it a promising solution for sustainable agricultural practices.

Key Processes in AI-Assisted Solar Drying Systems

The AI solar dryer operates through several key processes that enhance its efficiency and effectiveness. The first step involves the absorption of solar radiation by an absorber material within the solar collector. This absorber is typically covered with glass to prevent direct sunlight from degrading the food products, thus preserving vitamins, nutrients, and minerals¹². The absorber material, often made of aluminium due to its high thermal conductivity, absorbs heat from the sun and creates a warm environment. The hot air generated around the absorber is then drawn into the drying chamber using a blower¹⁴.

Next, forced convective heat transfer occurs, where blowers assist in moving the hot air from the absorber to the food material. This process ensures efficient heat distribution and facilitates the drying process. Once the hot air reaches the drying chamber, moisture evaporation takes place. The hot air absorbs moisture from the food, which is then removed through the blower. To maintain optimal drying conditions, humidity control mechanisms are employed. These involve removing humid air from the drying chamber and replacing it with drier air from outside, preventing moisture reabsorption into the product.

All these processes are automated using sensors and AI mechanisms. Finally, temperature control is crucial after the drying process. The product cools naturally as the dryer's temperature decreases after sunset or when solar radiation diminishes. Alternatively, some dryers use fans or ventilation systems controlled by Arduino programming to expedite the cooling process, ensuring the product remains at a safe temperature to maintain quality.

Components of AI assisted Solar Dryer

An AI-assisted solar dryer is equipped with a range of components designed to optimize the drying process by leveraging both solar energy and artificial intelligence. These components work together to enhance efficiency, precision, and product quality, making the drying process more effective and reliable¹³. Solar collectors are a critical component in solar dryers, and they come in various types, including flat-plate collectors, evacuated tube collectors, and concentrating collectors such as parabolic troughs or dishes. In our project, a corrugated aluminium sheet is utilized as the solar collector as shown in Fig.3. The design of the collector plays a significant role in its efficiency, with factors such as the material used (e.g., glass, metal), surface area, and orientation being crucial¹¹. Aluminium is chosen for its high thermal conductivity of 237 W/mK, which enhances the collector's ability to capture and convert solar energy effectively. Some advanced solar dryers may also incorporate solar tracking systems, which ensure that the collector remains optimally aligned with the sun throughout the day, thereby maximizing energy absorption and efficiency.

The drying chamber is a vital component of a solar dryer, and its design plays a crucial role in ensuring efficient drying. The layout of the chamber should be carefully planned to facilitate smooth airflow around the drying material, which is essential for uniform drying. Proper insulation is also critical, as it helps maintain consistent temperatures inside the chamber by reducing heat loss, thereby improving overall drying

efficiency¹. Additionally, airflow control mechanisms, such as vents or adjustable openings, are often incorporated to regulate airflow within the chamber. This allows for the optimization of drying conditions, ensuring that the product is dried effectively and consistently and a model is represented.

The Arduino R3, integrated with AI capabilities, plays a pivotal role in optimizing the drying process. It utilizes machine learning algorithms to analyse data from sensors, identifying patterns that correspond to optimal drying conditions. Based on this analysis, the AI controller makes real-time decisions to adjust critical parameters such as airflow, temperature, and solar collector orientation¹⁵. This dynamic adjustment ensures that the drying process is always optimized, leading to more efficient and consistent results. By leveraging machine learning and real-time data analysis, the system can adapt to changing environmental conditions, enhancing overall performance and product quality and it is shown.

The DHT11 sensor is a crucial component in the solar drying system, serving as a digital humidity and temperature sensor. It measures both the temperature inside the drying chamber and on the surface of the drying material, providing essential data for controlling the system's functions. Additionally, it monitors the humidity level within the chamber, allowing for the assessment of drying progress. This sensor works in conjunction with the Arduino, which processes the data and adjusts the system accordingly to ensure optimal drying conditions. By continuously monitoring temperature and humidity, the DHT11 sensor helps maintain a controlled environment that is conducive to efficient drying and high-quality product preservation. The DHT11 sensor shown in Fig.6 operates within specific technical specifications that ensure reliable performance. It requires a working voltage of 3.3V to 5.5V, which aligns with its operating voltage range. In terms of temperature measurement, it offers a resolution of 1°C and an accuracy of $\pm 2^\circ\text{C}$, with a measuring range from 0°C to 50°C¹⁸. For humidity, the sensor provides a resolution of 1%RH and an accuracy of $\pm 5\%\text{RH}$ within the temperature range of 0°C to 50°C. The humidity measuring range is between 20%RH and 90%RH at a temperature of 25°C. These specifications enable the DHT11 sensor to provide precise and reliable data, making it an effective tool for monitoring and controlling the drying environment.

In this project, blowers play a crucial role in managing airflow within the solar drying system. Two blowers are utilized to draw hot air from the solar collector into the drying chamber, ensuring that the heated air is efficiently distributed to facilitate the drying process. Additionally, another set of two blowers is used to remove humid air from the drying chamber, expelling it outside¹⁹. This dual blower system helps maintain optimal drying conditions by continuously circulating hot air and removing moisture, thereby enhancing the efficiency and effectiveness of the drying process.

The housing and impeller of the blowers shown in Fig.7 are made from thermoplastic PBT, UL94V-0, which offers high thermal stability and resistance to ignition. The blowers are powered by a DC brushless fan motor, known for its efficiency and reliability. The termination is achieved through a lead wire (UL 1007 AWG#24), with the red wire for positive voltage, black wire for negative voltage, and yellow wire for optional functions such as lock protection or rotation detection. The operating temperature ranges from -10°C to +70°C for sleeve-type bearings and -20°C to +80°C for ball-type bearings, ensuring that the blowers can operate effectively across a wide range of environmental conditions.

Insulating materials are crucial components in the drying chamber, ensuring thermal equilibrium with the surroundings. In this context, Aluminium Silicate foam is utilized due to its advantageous properties, including seismic heat resistance, low thermal conductivity, and low heat capacity. Additionally, it exhibits good elasticity of fibres and high temperature shrinkage resistance, making it suitable for various applications. These applications include insulation in furnaces, heating equipment, pipelines, and other lining or wall insulation. It is also used for heat sealing in furnace doors, lids, and roofs, as well as in chemical, electrical, and high-rise building insulation for fire protection⁵. The low thermal conductivity of Aluminium Silicate foam helps maintain consistent temperatures within the drying chamber, enhancing efficiency and product quality.

Aluminium Silicate materials, in general, are renowned for their excellent thermal insulation properties, high fire resistance, and mechanical strength. They are composed of silica, alumina, and other additives, which contribute to their durability and versatility in different environments. These materials are widely used in industrial and construction sectors for thermal and acoustic insulation, providing effective barriers against heat and sound. Their ability to withstand high temperatures and maintain dimensional stability makes them ideal for demanding applications, such as furnace linings and boiler insulation. Overall, the use of Aluminium Silicate foam in Fig.8 is used as an insulating material in the drying chamber ensures optimal thermal performance and enhances the overall efficiency of the drying process.

Solar dryers utilize solar panels as their primary power source, leveraging natural air convection or forced convection with air circulation fans to dry products efficiently. These systems are designed to maximize solar heat gain for optimal drying performance. Key components include a blower for heat supply, a solar collector to absorb solar radiation, and an exhaust fan to remove moisture²⁰. The system's performance has been tested with various products such as potato chips, tomatoes, and grains to achieve efficient drying times.

The solar panel in Fig.9 is used in this setup has specific specifications that enhance its effectiveness. It operates with a power output of 40 watts, making it suitable for powering the blower and other components. The panel's dimensions are 66.5 cm in length, 43.5 cm in width, and 3 cm in thickness, providing a compact design that fits well within the dryer's structure. The panel weighs approximately 3.8 kg, ensuring it is lightweight and easy to install. It operates at a voltage of 18V, which is compatible with the system's electrical requirements. The panel type is polycrystalline, known for its efficiency in converting sunlight into electrical energy. This setup allows for efficient energy conversion and reliable operation of the solar dryer.

Building Materials and Components

For the frame of the solar dryer, we utilized stainless steel square pipes due to their numerous beneficial properties that contribute to a robust and healthy structure. The original dimensions of the pipe are 25.4mm x 25.4mm x 6096mm. However, to create a square frame, the pipe is cut to precise dimensions of 280mm x 280mm x 280mm, ensuring a sturdy and compact structure shown in Fig.10.

Stainless steel is chosen for its corrosion resistance, which protects the frame from environmental degradation. It also offers strength and durability, providing a solid foundation for the dryer. Additionally, stainless steel has an aesthetic appeal, contributing to the overall appearance of the system. Its low maintenance requirements make it practical for long-term use, while its fire resistance ensures safety in high-temperature environments. Furthermore, stainless steel is environmentally friendly, as it is recyclable and non-toxic. Its versatility allows it to be easily shaped and adapted for various applications, and its longevity ensures that the structure remains stable and functional over time. These properties make stainless steel an ideal material for constructing the frame of the solar dryer.

In a solar dryer, the absorber plays a crucial role by capturing solar radiation and converting it into heat energy. This component typically features a dark-coloured surface or material with high absorptivity for sunlight, allowing it to effectively absorb solar energy. Once absorbed, the solar energy heats the absorber, which then transfers the heat to the air or fluid circulating through it. This process facilitates the drying of the product by providing the necessary warmth. For the absorber plate in our solar dryer, we have selected a corrugated aluminium sheet due to its high thermal conductivity. This choice ensures efficient heat transfer and maximizes the effectiveness of the drying process. The corrugated design of the aluminium sheet also enhances the surface area, allowing for better absorption and distribution of heat.

The tray in Fig.11 is a vital component of the solar dryer, serving as the platform where food particles are placed for drying within the drying chamber. These trays are made of aluminium mesh, which allows for

optimal airflow and heat distribution around the food, facilitating efficient drying. Each component of the AI-assisted solar dryer, including the tray, plays a crucial role in enhancing the system's functionality and efficiency. Together, they work in harmony to optimize the drying process, minimize energy consumption, and ensure that the final product maintains its quality and safety. The use of aluminium mesh trays contributes to this goal by providing a lightweight, durable, and easy-to-clean surface that supports the drying process effectively.

Construction and working of AI-Assisted Simple Solar Dryer

The drying chamber is constructed with dimensions of 300mm × 300mm × 400mm using the stainless-steel frame described earlier. A transparent glass panel is installed at the top of the chamber to allow indirect sunlight absorption through the corrugated aluminium sheet placed 20mm below it. This design ensures solar radiation is efficiently converted into heat for drying. Inside the chamber, two blowers are positioned to expel humid air during operation, maintaining optimal drying conditions. A solar panel powers the blowers and DHT11 sensors, enabling energy-efficient automation.

The system is controlled by an Arduino R3 board, which connects to the blowers and sensors. The Arduino IDE 1.8.19 software is used to program the board, allowing real-time adjustments to blower speed based on humidity levels detected by the DHT11 sensors. Humidity data can be monitored either via an LED display or by linking the Arduino to a PC. To enhance thermal efficiency, the chamber is insulated with aluminium silicate foam, minimizing heat loss. Aluminium mesh trays inside the chamber hold the food, facilitating uniform airflow and heat distribution for consistent drying results. This integrated design optimizes energy use, automation, and drying performance.

The prepared food items are placed inside the aluminium mesh trays, and the drying chamber is securely closed. The system is activated by initializing the Arduino R3 board, which triggers the automated drying process. The blowers automatically adjust their speed based on real-time humidity levels detected by the DHT11 sensors, ensuring efficient removal of moisture from the chamber. Once the food is fully dried, the system sends an alert through the connected PC or LED display. For added convenience, a buzzer can also be integrated into the Arduino setup to audibly signal the completion of the drying cycle. This automated workflow ensures precise control and timely notification, enhancing usability and energy efficiency.

Results and Discussion

We have developed an AI-assisted solar dryer that operates autonomously without human intervention. This system leverages the abundance of solar radiation to dry food and agricultural products efficiently, addressing a significant need in the current industrial landscape. The dryer is capable of handling approximately 2 kg of food products, taking into account their shape and size.

The integration of AI technology allows the solar dryer to function automatically based on pre-programmed data. The system uses an Arduino program to control the temperature and humidity levels required for optimal drying of specific food substances. A DHT11 sensor is employed to monitor temperature and humidity, providing real-time data that the AI system uses to adjust the drying conditions accordingly. Additionally, the blower speed is controlled by the Arduino, which adjusts the airflow to either increase or decrease heat as needed, ensuring that the drying process is optimized for the specific food being dried. This automated approach enhances efficiency, reduces labour requirements, and ensures consistent product quality.

Conclusion

This project presents a practical food dryer suitable for both domestic and industrial use. It leverages the DHT11 sensor to monitor humidity and temperature at regular intervals, ensuring optimal drying conditions. The blower, controlled by Arduino, facilitates frequent checks inside the dryer, enhancing drying efficiency. The Arduino programming is straightforward, allowing users to easily understand and modify the code to suit specific drying requirements. Since different food products have unique drying times and temperatures, the Arduino program can be adjusted to accommodate these variations. This flexibility makes the system versatile and adaptable for drying a wide range of food products efficiently.

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