THE STATUS OF SMART SOLAR DRYERS: REVIEW

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Abstract: Solar drying of agricultural products is one of the key components in food handling and processing. Over the years critical evaluation of different dryer designs has been explored. However, this review paper presents the status of smart solar dryers (SSD). The article is largely focusing on key transition stages in the solar drying technology. Advancement and functionalism of dryer automation systems have been given a particular attention in this paper. Electronic controllers and sensors adopted in previous (2016 to 2022) dryer designs have been highlighted. The paper presents a brief overview of the commonly applied dryer kinetics and models. Economic attributes of smart solar dryers have been discussed in this review. There has been tremendous improvement in the level of intelligence being applied in SSD. PID controllers are the most used electronic control systems in SSD. The application of Internet of Things (IoT) through Arduino is now gaining wide recognition in emerging drying technologies. Aspects of thin layer modelling are extensively applied in the designing and operation of smart solar dryers. Life cycle cost and life benefit cost are figures of merit widely considered in measuring economic viability of any drying technology.

Keywords: dryer, electronic sensors, smart, dryer models, kinetics, economic analysis.

1. INTRODUCTION

The world's population is growing at a faster rate and is projected to be above 9 billion by 2050 [1]. The increase in population growth is consequently raising demand for food. Research has also shown that 1.3 billion tonnes of food are lost annually[1]. In this regard, it is very important to keep a close focus at both food production and preservation. Notable advances aimed at reducing post-harvest losses, reducing drying time and improving quality of dried product have been registered in the drying technology.

The scientific art of drying agricultural products to improve their storage life dates back to ancient days [2]. Drying is a process of removing moisture from agricultural produce or food products through mass and heat transfer [3]. Different categories of solar dryer designs have been presented in literature. Solar dryer designing is largely influenced by requirements of the material to be dried (specimen drying kinetics) and budget allocation [4]. The advancement in electronics and technology has given birth to smart solar dryers (SSD). Smart solar dryers are dryers whose key system functionalities are highly monitored and controlled by electronic devices such as controllers and sensors [5, 6]. The application of electronic sensors and controllers improve flexibility and performance of solar dryers. Despite the fact that some dryer control systems may comparatively appear expensive, the gains that accompany sensor and control systems like improved drying time, product quality and flexible system offset any additional cost.

1.1. Organisation of the study

This paper has been organised as follows: Section 1 presents introduction. Section 2 discusses three major classes of solar dryers. Section 3 presents key transition stages in solar drying technology. Section 4 is devoted to SSD kinetics and models. Section 5 presents various aspects of solar dryer automation. Section 6 presents economic analysis of solar dryers. Section 7 presents identified gaps, future research areas and conclusion.

1.2. Motivation of the study

There are several review studies that have been done in the field of solar drying. However, very few studies dealt with smart solar dryers comprehensively. Critical evaluation on the application of electronics to the drying industry is key to enhancing performance of solar dryers. The motivation to carry out this review is based on the following contributions:

- The study on advances made in the drying technology is very significant in promoting solar dryer performance hence promoting food security.
- Presentation of key transition stages that the drying technology has undergone.
- Detailed discussion on the commonly used dryer kinetics and models will promote knowledge on suitable models for SSD and enable future researchers work towards their improvement.
- Based on dryer automation, various types of electronic sensors and controllers have discussed to enhance understanding on the linkage between electronics and solar drying, and appreciation on the level of intelligence currently been applied in SSD.
- Demonstration on significant contributions that advancements in electronics have made towards improving dryer performance.
- Focusing on economic viability of SSD, various economic figures of merit very essential in economic analysis have been presented.

2. CLASSES OF SOLAR DRYERS

[1] argues that solar dryers can be categorized based on size, system design and mode of solar energy utilization. [7] identified direct, indirect and mixed mode as three types of solar dryer based on specimen drying kinetics, air movement, insulation material and contribution of solar energy. In a similar study [8] categorized solar dryers as convective, spray, freeze and osmotic drying based on air movement and dryer design. This study identifies eight types of solar dryers based on three classifications as shown in Figure 1.

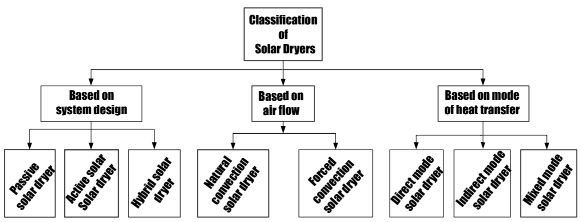

Fig. 1. Classification of solar dryers

2.1. Based on heat flow

Convective heat transfer takes place due to both molecular motion and microscopic motion of the fluid parcels. Solar dryers in which air flows naturally due to density gradient are classified as natural convective solar dryers. Solar dryers in which air flows due to pressure difference resulting from a pump or fan are known as forced convection solar dryers. In most cases the distribution of heat in forced convective solar dryers is a result of both density gradient and pressure difference [9]

2.2. Based on mode of heat transfer

When the incoming solar radiation is directly incident on the agricultural produce being dried, a dryer is considered as a direct mode. In direct mode solar dryers, solar radiation passes across a transparent covering material and is later absorbed by the product and the surrounding absorbing surface [7].

On the other hand, indirect solar dryers do not expose the agricultural produce being dried to direct solar radiation. Air is heated in a special solar collector (absorber) and then ducted to the drying chamber where the actual drying process takes place. Often, a chimney is introduced to improve airflow. Indirect solar dryers are widely applied in drying crops whose vitamin content can adversely be affected by direct sunlight like vitamin A in carrots [7].

A combination of both direct and indirect modes mechanisms produces a mixed mode solar dryer. In this design, heat for the drying process is supplied by both direct solar radiation incident on the material being dried and preheated air from the solar collector [10]. Mixed mode solar dryer is also referred to as solar tunnel dryer.

2.3. Based on system design

Dryers in this category are divided into three sub-categories namely; passive, active and hybrid solar dryers. Passive solar dryers are dryers that operate without reliance on external devices and usually made up of natural convection solar dryers. The construction and design of solar energy dryers allow air flow and heat transfer take place solely based on the laws of thermodynamics and are less energy demanding. This category is suitable for drying agricultural produce with low moisture content [7].

Active solar dryers are dryers that utilize external devices such as pumps, fans, blowers and heaters to enhance air flow and heat transfer. Fans, blowers and heaters are driven by external energy and that is why active solar dryers are referred to as energy intensive dryers [11]. This category incorporates mechanics of both forced convection and mixed mode solar dryers.

3. TRANSITIONS IN SOLAR DRYERS

The drying technology has seen a transition from the ancient open-air sun drying to the modern smart solar dryers as presented in Figure 2. The transition in the drying technology is as a result of continued increase in research activities in mechanical and electrical engineering (Renewable energy). Dryer designs, performance and efficiency have kept on improving within this transition.

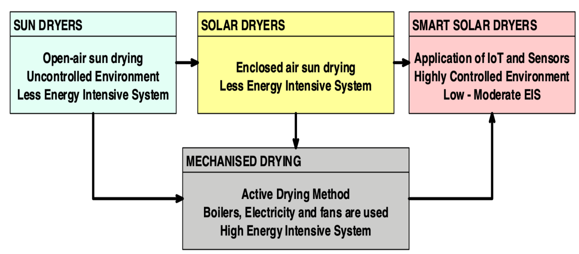

Fig. 2. Transitions in solar drying technology

3.1. Open air sun drying

Sun drying is the most primitive drying technology where agricultural produce are spread on the ground to receive direct heat from the sun [12]. Open-air sun drying is commonly used across the globe because it is very cheap and a less energy intensive method.

However, there is no control on the external factors such as wind, rain, dust, pests, rodents and contamination that reduce the quality of the dried products, consequently leading to loss of income to farmers [1]. Figure 3, shows agricultural crops being dried directly in the open-air sun.

Fig. 3. Open-air sun drying [1].

3.2. Solar drying

Solar drying is an improvement to open-air sun drying. In solar dryers, agricultural produce are placed in a controlled environment where they receive heat from the sun directly or indirectly [13]. The rise in the adoption of solar dryers across the globe is based on the system's control over internal and external forces and a relatively improved efficiency [14]. In most cases solar dryers operate in a passive mode and require less energy to dry agricultural produce as shown in Figure 4.

Fig. 4. Elementary solar drying [1].

3.3. Mechanised drying

Mechanized drying is applied to improve performance of both the open-air sun drying and solar dryers by introducing boilers, electricity, blowers and fans. Dryers in this category operate in the active mode and are usually high energy intensive [14,16,17]. Mechanized dryers are well suited for drying agricultural products with high moisture content such as fish. The key advantage of mechanized drying is the reduced drying time [10].

3.4. Smart solar dryers

The dawn of 21st century has seen increased research activities in smart solar dryers (SSD) [18,19]. Application of electronics and Internet of Things (IoT) to improve dryer performance has been investigated and presented by several authors [13, 7, 20, 21, 17, 2, 22].

The introduction of electronic sensors and controllers in the drying technology has significantly enhanced the intelligence in controlling drying kinetics of the drying chamber [23]. Most of the smart solar dryers operate in the active mode as shown in Figure 5, and their energy demand ranges from low to high depending on design. Smart solar dryers may either incorporate all design features of mechanized solar dryers [16] or features of ordinally passive solar dryers [24].

Critical review of literature show that previous designs of smart solar dryers were specifically designed to dry a particular agricultural produce of a particular food group; fruits [25, 21], fish [16], roots and tubers [19], grains and cereals [13, 2], leafy vegetables [26], wood and herbs [27, 28]. Efficient drying of each of the different groups of agricultural produce demands appropriate settings of the required SSD drying kinetics and environment.

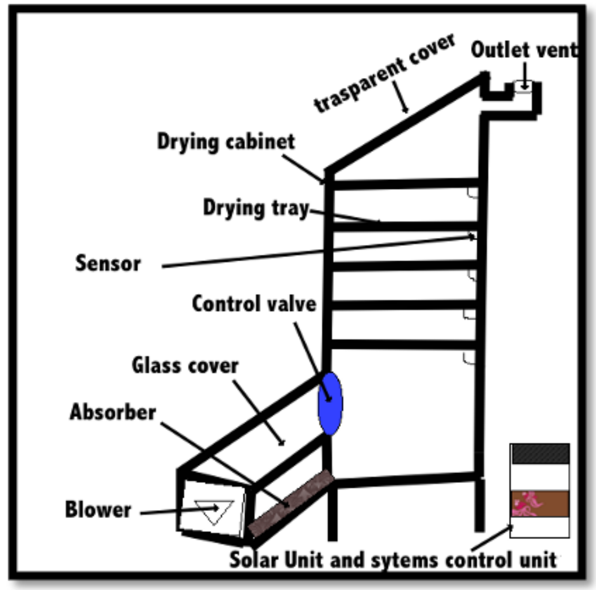

Fig. 5. Smart solar dryer

4. DRYER KINETICS AND MODELLING

Attributes of both the drying chamber and the product to be dried affect the drying process. The drying process of agricultural products is fundamental to the selection of an appropriate SSD design and process optimization [29]. Temperature, relative humidity, air velocity and direction determine the quality of the environment in the drying chamber. Similarly, moisture content, structure and size of the agricultural produce influence drying and falling rates. [30] argue that, surface diffusion on the pore surface, liquid, or vapour diffusion due to moisture concentration differences and capillary action in granular and porous agricultural produce due to surface tension are three main drying mechanisms. Hygroscopic products dry at constant rate. The surface of the product being dried is greatly affected by constant rate drying period, physical formation of the product, temperature, drying air velocity, direction of air flow and relative humidity under surface diffusion [25,26,27]. On the other hand, internal conditions such as moisture content, temperature and structure of the product play a crucial role in the falling rate periods. [31] advance that color parameter of the dried product is very essential in some food families like fruits, leafy vegetables, roots and tubers. Excessive color change may destroy some vitamins and food nutrients.

Vapour diffusion due to moisture concentration deference and internal product conditions leads to second falling rate periods. Vapour or liquid diffusion controls the drying process of agricultural products during falling rate periods. At this stage the transfer of moisture content from the product is governed by diffusion. [32] argues that temperature is the most significant factor that influences drying rate of vegetables. The establishment of good drying kinetic model permits strict quantitative monitoring of physico-chemical changes that occur in the drying process [33]. Thin layer modelling has recently gained wide application in the drying of agricultural produce due to its simplicity to use [34]. Thin layer models are classified as theoretical, semi-theoretical and empirical models [34]. Theoretical model considers the application of the Fick's second law of diffusion. Semi-theoretical model includes page model, Newton model and diffusion model. On the other hand, empirical model derives a relationship between moisture ratio and drying time but neglect the basics of the drying process. It is usually applied to the external drying conditions of the experiments and is used to describe the characteristics of the parameter. Wang and Singh model, and linear model are common examples of empirical modelling. [35] applied page, Lewis, Henderson-Pabis and diffusive models to predict the drying curves. Among the tested thin models, Henderson-Pabis and diffusive models displayed best fitting performance and statical evaluations [35]. In a similar study, [36] evaluated the performance of diffusion model and characteristic drying curves. The study highlighted that both diffusion models and characteristic curves predict responses to the most changes in the external conditions. A summary of thin layer modelling techniques is illustrated in Figure 6 as presented by [30, 29, 31].

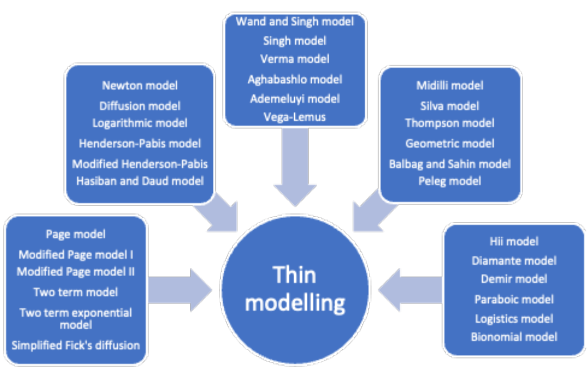

Fig. 6. Solar dryer thin modelling techniques

5. SOLAR DRYER AUTOMATION

Over the years, the level and complexity of intelligence being added to solar dryers has kept on improving. System control and conditioning in solar dryers is aided by electronic controllers and sensors [5].

5.1. Control unit

The control mechanism in smart solar dryers is enabled by micro-controllers, sensors, and Internet of Things (IoT). Microcontrollers are electronic devices that are used to control dryer operating kinetics such as heating level, speed of heated air in the drying chamber, speed of the exhaust fan, temperature of the chamber, time intervals, setting on and off of the exhaust fan, blower and electric heater [25, 37].

Several solar dryer control units have been tested; PID controller [12], actuator jack [19], Arduino [21], ATMEGA controllers (89C52) [24], PI and Fuzzy controllers [22], PIC controllers (P1C16F877A) [37] and Process Logical Control (PLC) [38]. [22] argues that PI controller is best suited for controlling drying kinetics of solar dryers for they provide a balance of complexity and capability that is suitable in process control applications. Arduino boards that utilize AVR ATMega microcontrollers have gained wide application in drying technology in the 21st century as displayed in the works of [39, 40, 23, 21, 15].

5.2. Electronic sensors

The advent of electronic sensors has contributed significantly towards improving performance and efficiency of various electronic gadgets including solar dryers [41, 6]. A sensor is a device that detects specific changes in the environment to generate a signal that insinuates a reaction [42]. Electric sensors translate a stimulus into an electrical signal that is processed into a meaningful end-user information. Sensor selection is very critical for efficient performance of solar dryers. Appropriate sensor technology is key to improved system performance. [43] argue that sensor selection must be based on suitability, capacity and limitations for that designated application. Sensors applied in the drying technology must be sensitive, reliable, durable, flexible, accurate, linearity of response, quick response and recovery time, and reproducible regardless of the drying environment [43]. Similarly, cost, size, circuit complexity, output reproducibility and contamination resistance of a sensor are of a great importance in solar dryer sensor selection.

There are numerous categories and applications of electronic sensors presented in previous studies. However, this paper will only focus on electronic sensors commonly applied in the drying technology. Temperature, humidity and mass detection sensors are among the frequently applied sensors in the drying industry.

5.2.1. Temperature sensors

Devices that generate a signal in response to changes in temperature are called temperature sensors [14]. Signals are generated by comparing ambient temperature and temperature in the drying chamber. Four distinct categories of resistors commonly applied in electronic devices include, thermistors, resistance temperature detector (RTD), thermocouples and semiconductor-based temperature sensor. A thermistor is a resistor that is sensitive to thermal energy and exhibits a continuous small-incremental change in resistance with respect to variations in temperature. Usually, resistance drops with an increase in temperature. A resistance temperature detector (RTD) is an electronic sensor that varies its resistance with temperature [42]. Thermocouples are resistors made up of two wires of two different metals that are electrically joined at two points. Voltage variations between these two dissimilar metals show proportional changes in temperature. Semiconductor-based temperature sensor is made up of two identical diodes that have temperature-sensitive voltage against current characteristics used to detect changes in temperature.

5.2.2. Humidity sensors

Solar dryer sensors that send signals in response to changes in the amount of water vapor in air are called humidity sensors. Humidity sensors exist in a wide range of categories. [43] classifies humidity sensors as capacitive, resistive, thermal, gravimetric, optical and piezoresistive. In a capacity humidity sensor, the electrical permittivity of the dielectric material varies with changes in humidity. Similarly, the material resistivity of a resistive humidity sensor changes with respect to the changes in humidity [42]. The pressure of water facilitates conductivity in non-metallic conductors. Thermal conductivity humidity sensors measure thermal conductivity of both dry air and water vapour (absolute humidity). Two thermistors with negative temperature coefficient are arranged in a bridge circuit form. The difference between the resistances of the two thermistors is directly proportional to the absolute humidity. Other dryer humidity sensors include optical fiber, microwave, dry and wet globe temperature and dew point [43].

DTH 22 [2], LM 35 [44, 21] are some of the most commonly used sensors in the drying technology. The sensors detect changes in temperature and humidity and send this information to the control unit for processing [14]. In a solar dryer designed by [12], load cells were used to monitor weight of the dried products in the drying chamber. Data loggers that contain sensors to receive information from the drying environment are oftentimes used in solar smart dryers [25].

5.3. SSD control and conditioning

The level of control and conditioning in solar dryers depends on dryer design and the type of agriculture produce being dried. Some advanced control systems [10,22] use fuzzy controllers. Fuzzy controller contains two key components; fuzzy rule and membership function. The fuzzy system set contains defined semantic labels that are easily read by humans [22]. The performance of fuzzy controllers is comparatively better than PI controllers.

In most smart solar dryers, conditioning of the drying chamber is achieved by controlling temperature and humidity [25]. Temperature and humidity are controlled through switching on and off an exhaust fan or blower and adjusting the speed of air in the drying chamber. Very few smart solar dryers have their control extended to adjusting the orientation of the drying cabinet and solar collector [19], or switching the dryer from direct mode to indirect mode or dual mode and vice versa. Extensive literature review carried out in this study has revealed that previous SSD designs did not have a sample analyzer to get psychometric data of a particular feedstock sample and send it to the controller to enable appropriate settings of the drying chamber. Furthermore, no design in previous studies considered extension of control functions to adjusting dryer operation from indirect mode to direct mode or mixed mode and vice versa, depending on the amount of available insolation and desired drying kinetic of a particular agricultural product. A summarized analysis of dryer control systems and conditioning mechanisms for the past six years is presented in Table 1.

Table 1. Analysis of dryer control system and conditioning mechanism

Author	Description	Control System	Conditioning	Food product
[12]	Influence of drying temperature	PID controller, sensors: temperature & humidity, load cells	Monitoring temperature, air velocity & weight	Grain and cereals: corn
[39]	Design consideration of smart solar dryer	Arduino (MEGA 2560), sensors: temperature & humidity, load cells	Monitoring and controlling weight, air flow, humidity & temperature	Roots and tubers: ginger
[19]	Design, construction & testing of automated solar dryer	Electronic position controller, sensor: Reed switch	Varying the angle of the collector with respect to the sun	Roots and tubers: Cassava chips
[40]	Real-time conditioning and monitoring of solar drying	IoT based controller: AT Mega 16, sensors: flow, temperature and humidity	Monitoring and controlling of air velocity, weight, voltage current, temperature & humidity	Not provided
[25]	Automated solar powered hot-air supplemented dryer	Controller: Not specified, Sensors: Temperature & humidity, data logger	Setting on of DC fan & electric element, controlling temperature, presetting stored information	Fruits: Yams
[44]	Automated solar dryer using Sapota fruits	Arduino Uno, Sensors: LM35	Monitoring and controlling of air velocity and temperature	Fruits: Sapota
[14]	Solar dryer with temperature controller	Arduino Uno, sensors: LM 35	Monitoring and controlling temperature	Fruits, vegetables: red chilli, Oyster mushroom, pomegrate
[16]	Semi-automated gas fired fish dryer	PID controller, sensors: temperature	Monitoring and controlling temperature	Fish
[2]	An automated solar biomass hybrid dryer	Raspberry PI microcontroller, sensors: DHT 22	Controlling temperature, humidity and air flow	Fish
[24]	Solar powered automated fruit drying system	89c52 controller, sensor: LM 35	Controlling air flow, temperature & time indication	Fruits
[22]	Power optimization & temperature control in solar automated dryer	PID controller & fuzzy tuned controller, sensor: temperature	Controlling temperature	Fruits: Cardaman

6. ECONOMIC EVALUATION OF SSD

Designing and implementation of any solar dryer must seriously consider the accompanying economic attributes. In addition to good system designing parameters and kinetics, a solar dryer must be economically viable for easy accessibility, maintenance, application, and optimized profits. Several economic analysis techniques have been explored in the drying technology, life cycle cost (LCC), life cycle benefit (LCB), cost-benefit analysis (CBA), net present worth or value (NPW/NPV), annuity (A), internal rate of return (IRR), payback period (PBP), [45], least cost energy (LCE), annualized life cycle or cash flow [46] and annual depreciation effects [47]. [48, 49] argue that a solar dryer must be economically viable. Much as the adventure of smart solar dryers indicates a milestone in the drying industry, robust economic evaluation is always required to appreciate their economic performance relative to convectional dryers. There is usually a cost attached to every technological advancement in any subject domain. Apart from economic variables associated with an ordinally dryer architecture and agricultural products, the hardware and software used in the implementation of a smart solar dryer attracts other economic figures of merit. The cost of a smart solar dryer varies as you move from a simple elementary smart solar dryer to a more complex smart solar dryer. A simple elementary solar dryer with limited automation functionality and intelligence is relatively cheaper to implement. However, the limitation in the dryer intelligence and flexibility may negatively affect dryer efficiency and quality of the dried agricultural produce. Reduced dryer efficiency and quality of dried agricultural consequently affect smart solar dryer's profit margin. On the other hand, complex smart solar dryers with advanced system automation and intelligence are more expensive. The enhanced intelligence and flexibility promote dryer efficiency and quality of dried products hence creating an offset between costs and profits.

[46] applied life cost method to analyze solar process economics. Life cycle saving method considers time value of money, complete costs range and design criteria and variation in design factors. Complete cost is the summation of all costs incurred on hardware items and labor during the installation of the equipment. Several solar dryer attributes like collector size, material and adopted electronic technology affect the cost of the dryer and drying process. [50] evaluated economic variability of an inclined solar dryer for fruits and vegetables. Life cycle cost and life cycle benefit techniques were used to determine the viability of the proposed dryer in comparison with conventional solar dryers. Results showed that the inclined dryer was economically viable. Similarly, [51] analyzed economic fitness of a solar dryer with a phase changing material. The dryer was designed to operate with both sensible heat storage and latent heat energy storage systems. The drying system proved profitable with a payback period of 0.578. [52] compared the performance of various selected solar dryers using the annualized cost, the net present worth of annual savings and the present worth of cumulative savings. The study considered, solar tunnel dryer, solar cabinet dryer, solar conduction dryer, corrugated solar conduction dryer and corrugated and electrically backed solar conduction dryer. Corrugated solar conduction dryer exhibited the best economic performance than the rest of the dryers.

7. CONCLUSION

Solar dryers have gone through key transitions from open-air sun drying to smart solar drying. Advancements in the level of intelligence being applied to smart solar dryers have greatly improved dryer performance and efficiency. Arduino boards that utilize ATMEGA controllers in IoT have gained wide recognition and application in the drying technology. PID controllers are so far the commonly used controllers in dryer automation. Control functionalities in most dryers are aimed at motoring and regulating temperature and humidity. Life cycle cost and life benefit cost have been extensively applied in assessing economic viability of SSD. Economic figures of merit associated with SSD indicate that SSD compete very well with conventional drying technologies.

Research gaps and future directions:

The level of automation and intelligence in the previous and current dryers is limited to temperature, humidity and position of the collector. This paper suggests that further research be carried to explore other automation features that may be introduced like switching from direct mode to indirect mode or dual mode and vice versa by closing and opening of dryer compartments. Furthermore, most SSD are designed to dry one or a specific group of agricultural produce as such they only accommodate limited number of agricultural products. Future researchers should consider developing universal smart solar dryers with a capacity of accommodating crops from all groups of agricultural products.

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