Performance Investigation of an Inflatable Solar Dryer with Steel-Can Solar Air Heater for Drying Coffee and Corn

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Abstract-Coffee and corn are the two most important crops in the Philippines. One of the most critical stages, where crop management can be improved, is drying. In coffee, a moisture level of 12% is optimum for minimizing quality degradation throughout lengthy storage periods, whereas, corn requires a moisture content of 13%. With the demand for simple and cost-effective drying technologies, an Inflatable Solar Dryer (ISD) was created and adapted using a Hohenheim-type solar tunnel and Salvatierra-Rojas' study. A mesh wire served as a drying space and was placed inside the ISD to avoid moisture condensation. A clear polyethylene (PE) film is attached to a reinforced black Polyvinyl Chloride (PVC) film by a zipper to produce a drying tunnel. The tunnel does not require a foundation because the pressure generated by a solar-powered fan sufficiently stabilizes it. The ISD also incorporated steel cans as solar air heaters to boost the temperature of entering air into the chamber and gradually provide heated air temperature to the bottom parts of the crops. Crops were scattered on the mesh wire and blended with a rake. Drying in the open sun was also done in parallel for comparison purposes. After protracted drying, both crops reached the required moisture content. The trial found that the weight of both crops was affected by the drying duration. The difference in weight for coffee is 1.1kg, while for corn is 0.5kg exhibiting a significant advantage in ISD.

Keywords-postharvest management; corn; coffee; inflatable solar dryer; solar air heater; solar-powered fan

I. INTRODUCTION

Agriculture is vital to the economies of developing countries as it is the primary source of food, currency, and employment for rural populations. On the other hand, agriculture and land-use reforms are critical for achieving food security, poverty alleviation, and overall sustainable development. According [1], farming employs 28.4% of the workforce in the Philippines and contributes an average of 10.18% of the country's GDP. Given this percentage, the Philippines continues to import agricultural products. Corn and coffee are two essential crops imported in the Philippines. According to the Department of Agriculture (DA), the Philippines imports 75,000 MT to 100,000 MT of dry coffee beans from Vietnam and Indonesia each year at P7 billion to P10 billion [2]. At the same time, corn imports averaged 604,000 tons from 2017 to 2019. Based on the data from the United State Department of Agriculture (USDA), corn imports are predicted to remain steady from 2021 to 2022 as a result of improved local production and ample feed grain inventories [3], while the country's coffee production would increase to 214,626 MT by 2022, based on the Philippine Coffee Roadmap [2]. By undertaking pest and disease management activities and providing seeds, fertilizers, and pesticides, many government agencies along with the private sector are working to boost the country's corn and coffee production. Postharvest management, such as the provision of dryers, was, on the other hand, negligible, even though it is equally vital in the entire production of crops. According to [4], post-production losses in the country occur mainly in handling and drying, resulting in delayed, incomplete, or inefficient drying.

Open Sun Drying (OSD) was introduced for agricultural product preservation and storage. This method of drying is still widely used even today. However, OSD faces many inherent limitations like overexposure, which causes food damage, high losses in yield production due to insects, rodents, and birds, longer drying time, and unpredictable climate conditions [5]. In the Philippines, OSD is the main practice of the farmers. In fact, with the absence of drying facilities, many crops, including coffee beans and corn, are dried on highways or road pathways where vehicles may run over and ruin the products. Other corn and coffee producers, on the other hand, choose to trade their crops immediately after harvesting to prevent farm losses and additional expenses. It can be noted that freshly picked coffee beans and corn when sold will have a low farm gate price as compared to dried crops. Locally, newly gathered, or wet corn is priced at Php.12.00 at the farm gate, whereas dry corn with an optimal moisture content of 13% is priced at Php.17.00. The farm gate price for newly picked coffee beans is Php.30.00, while the farm gate price for dry coffee with an optimal moisture content of 12% is Php.110.00. With such

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disadvantages and differences between the price of wet and dry crops, the need for solar dryers and their implementation has drawn the attention of researchers.

Many types and models of solar dryers have been studied and developed worldwide. However, in the Philippines, there are limited published articles about the implementation of solar dryers. The latest solar dryer study done in the country was the ISD by Salvatierra-Rojas in 2017, using rice as the commodity [6]. The dryer gives a promising result in drying rice in humid climates like in Philippines. Furthermore, the study demonstrates that the ISD is an ideal dryer for small-scale farmers due to its low-cost materials and simple operation. Therefore, the goal of this study is to employ such an ISD to dry corn and coffee beans. The results were compared to the performance of OSD in terms of drying time and final weight when reaching the desired moisture content of 13% for corn [7] and 12% for coffee beans [8]. Recycled steel-can Solar Air Heater (SAH) was integrated into the ISD to increase air inlet temperature and determine its contribution to the ISD by closely monitoring the inlet, mid, and inside humidity and temperature. Mesh wire was also placed inside the ISD to prevent condensation.

II. MATERIALS AND METHODS

A. *Design of the Inflatable Solar Dryer*

The ISD was based on [6], which was constructed from the Hohenheim-type solar tunnel [9] that has been developed and commercialized to dry different agricultural products in different climatic conditions. Unlike the Hohenheim-type dryer and the Salvatierra-Rojas study, which laid the grains barely in black PVC films inside the chamber, this study incorporated an elevated mesh wire inside the ISD chamber to allow double pass of hot air into the lower and upper part of the dried products and to allow better circulation of the moist inside the chamber. The dryer is still collapsible, just like in [6].

The ISD drying chamber comprises 150μm UV-transparent polyethylene (PE) film and is joined to a 0.52mm reinforced black PVC film by a heavy-duty zipper. A heavy-duty zipper is positioned and sewn along the margins of both plastic layers. The entire unit is placed directly on the ground. The tunnel does not require structural support and is effectively stabilized by air pressure from inflation. One 220V solar-powered fan blows air into the tunnel, which is then expelled through the opposite side's vents. The inclusion of renewable energy was based on the findings of [6], which recommended that more research should focus on incorporating photovoltaic power supply for the ventilators to enable off-grid operation [6]. The chamber's tested drying space is 2.5m long and 1.5m wide. To prevent moisture condensation inside the ISD chamber, this study used a 15×15cm mesh wire supported by four pieces of 2×2ft. wood. The crops were then spread at the height of 20mm on top of the mesh wire and were mixed with a rake to minimize overheating of the top layer exposed to the sun.

B. *Design of the Solar Air Heater (SAH)*

The SAH was used in the study to raise the temperature of the air entering the ISD. The SAH was made out of 390ml steel cans. For the first layer, 49 pieces of steel cans were arranged vertically in 7 groups and for the second layer, 30 pieces of the same cans were laid in 5 groups. There was a gap between the cans for the second layer to allow air circulation inside the SAH. The SAH's frame was made of a 5mm plyboard and was measured to be 0.905m in length, 0.6m in width, and 0.2m in height. The SAH has round perforations on one end to allow the incoming air to pass through. On the opposite end of the SAH, a single rectangular hole connects to the fan and ISD through a 10mm foam insulator. The SAH was painted black as a coating material to increase its thermal operation [10]. The SAH's top cover and glazing system were made of 5mm transparent glass to restrict the steel cans' radiant and convective heat absorbance. Four heavy-duty caster wheels were installed at the bottom of the SAH to make it portable and easy to transport.

A two-layer design composed of insulator foam and black PVC film was stitched together, and magic tape was attached to link the sides and form a tunnel to connect the SAH, fan, and ISD, as shown in Figure 1. Table I shows the design parameters, such as the overall size of the SAH, ventilator size, and the overall size of the ISD.

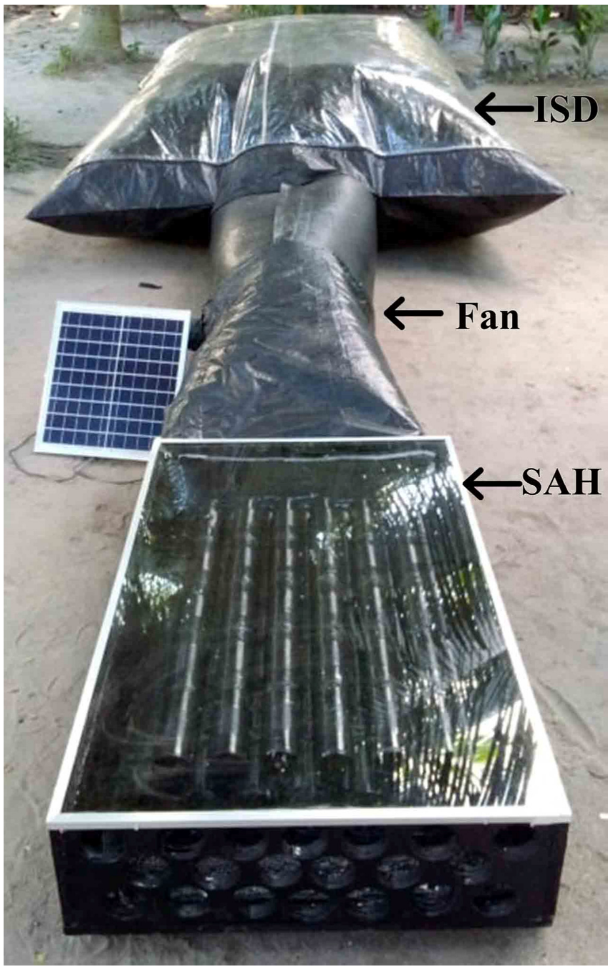

Fig. 1. Design of ISD and integrated SAH with a solar powered fan.

TABLE I. DESIGN PARAMETERS OF THE EXPERIMENTAL SETUP

Design parameters	Details
Solar Air Heater (SAH)	
Type	Steel can solar energy heat absorber
Overall size of the SAH	0.905m length × 0.6m width × 0.2m height
Overall size of the steel can heat absorber	0.755m length × 0.6m width × 0.15m height
Ventilator	
Type of ventilator	Solar-powered fan
Diameter of ventilator	16 inches
Ventilator	220 V AC/DC
Airflow rate	1.7 m/s
Inflatable solar dryer (ISD)	
Overall size of the ISD	2.5m length x 1.5m width
Height of the inflated tunnel	0.75m
Mesh wire drying space	
Overall size of the drying space	2.1m length x 1.1m width
Height from the ground	0.15m
Capacity (fresh)	100 kg

C. Drying Experiment

The dryer was used in the Philippines' Sultan Kudarat province (6.5069° N, 124.4198° E). The dryer was set up in the middle of a paddy field that was completely unoccupied. The crops used in the trials were Robusta coffee and yellow corn. Each experiment trial was conducted a day after the crops were harvested. The initial moisture content of both crops and their initial weight were measured at the start of the drying experiment. Similarly, before the crops were set aside throughout the night or during heavy rains, the weight and the moisture content were tested again to see how much had changed over the drying period within the day. The trial began at 7 a.m. and ended at 5 p.m. every day, i.e. for a daily duration of 10 hours. The coffee had a moisture content of 40.5% on a wet basis, whereas the corn had 38.9%. During each experiment trial, the solar-powered fan was permitted to run continuously within the drying duration. At 1-hour intervals, the crops were dried and scattered with a rake. Each dryer had three batches of crops to dry. The OSD was used as a control method, with each batch containing 16.3kg of coffee beans and 16.9kg of corn. The sample crops were spread out on a black PVC film next to the ISD with a bulk height of 20mm. The crops in the OSD were mixed with a rake at the same time as the ISD. The crops were kept aside throughout the night or when there was severe rain but were dried the next day until the ideal moisture content for each crop was reached.

D. Instrumentation of Drying Experiments

To evaluate the study's goal, four essential tools were used. A 25kg capacity digital weighing scale was used to determine the initial and final weight of the crops, whereas a digital moisture content meter (AR991 KERRO Smart Sensor Digital Grain Moisture Meter) was used to determine the moisture content. A self-logging humidity and temperature sensor (BSIDE Mini USB Humidity Temperature Data Recording Logger) was mounted on the inlet, in the middle (in the fan, where the wind is blown), and on the ISD chamber to determine the temperature and relative humidity as shown in Figure 2. When linked to a computer, data were logged every 10s and were automatically generated and exported.

E. Statistical Analysis

T-test experimental design was conducted using the Excel statistical software, with p values less than 0.05 considered significant.

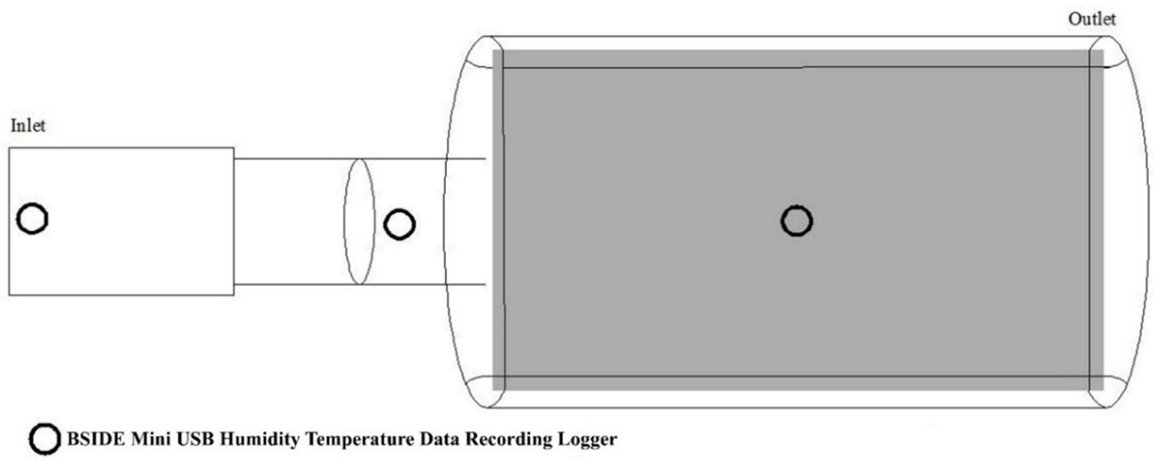

Fig. 2. Position of humidity and temperature sensor top view

III. RESULTS AND DISCUSSION

A. Temperature and Relative Humidity (SAH, Fan, ISD)

The humidity and temperature loggers were positioned in three different locations in the dryer. The first location was in the SAH, where there was incoming air, the second was next to the solar-powered fan to see if the steel can SAH could boost the incoming air temperature, and the third was on the top of the crops inside the ISD. The dryer's ambient temperature varied from 31 to 46ºC, 31 to 51ºC, and 31 to 70ºC respectively from the SAH air inlet, alongside the fan, and within the ISD. Figure 3 shows the air temperature and humidity profile within the dryer over 10h, using the chosen intervention phase data. In general, there was a progressive temperature rise between the

SAH input and the fan, but the most increase was between the fan and the ISD. The highest temperature of the day was between 11 a.m. and 2 p.m. However, the temperature in the three places gradually declined after sundown, eventually approaching ambient temperature. The temperature rises in the dryer continued to be minimal due to evaporative cooling provided by the crops and more significant convective losses due to a higher difference in temperature out from ambient air.

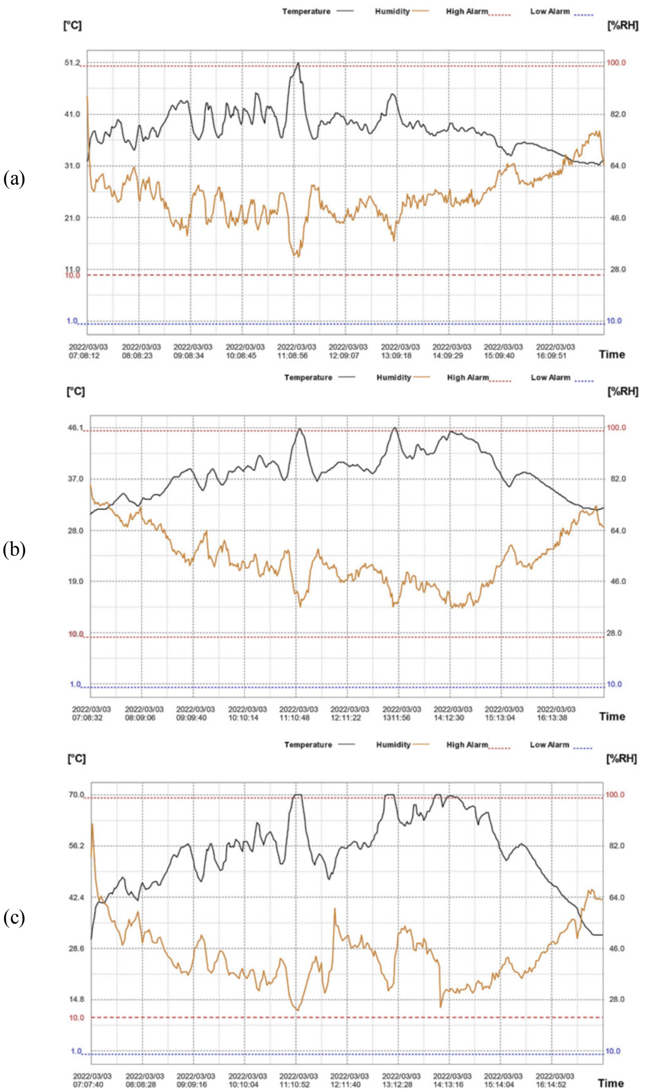

Fig. 3. The dryer's temperature and humidity at (a) SAH air inlet, (b) the fan in the middle, (c) ISD at the top of the crops.

B. Moisture Content and Drying Behavior

The moisture content of the crops during ISD and OSD drying is shown in Table II. Under ISD, coffee with an initial moisture content of 40.5% reached the ideal moisture content of 12% in 3 days (27h), while in OSD, coffee with the same initial moisture content dried to 12% moisture content within 5 days (47h). For the corn, the crops placed in the ISD with an initial moisture content of 38.9% dried to the target of 13% within a day, while when drying under OSD, the crops with the same initial moisture content dried in 2 days (14h). The target moisture content of 12% for coffee and 13% for corn may be easily obtained by continuously drying. However, when the crops were retrieved from the dryer at night, remoistening occurred, resulting in an increase in moisture content overnight. On the other hand, remoistening becomes minimal to none once the target moisture content is obtained.

TABLE II. MOISTURE CONTENT IN ISD AND OSD

Products	The moisture content of the products		
	Fresh product	ISD	OSD
Coffee	40.5%	12.00%	12.1%
Corn	38.9%	12.25%	12.76%

C. Weight

The results of coffee weight shown in Table III and Figure 4 revealed a significant difference with a p-value of 0.018 under ISD and OSD, with a difference of 1.1kg in the final weight of coffee after reaching the desired 12% moisture content. However, corn weight results in Table IV show no significant difference. The difference in the final weight of corn after reaching the 13% moisture content is 0.5kg with a p-value of 0.09. This means that the product's drying time impacts the final weight when it reaches the target moisture content.

TABLE III. T-TEST OF WEIGHT OF COFFEE

Dryer	Mean	SD	Diff.	t	P-value	Interpretation
ISD	7.7	0.17	0.35	3.89	0.018	Sig.
OSD	7.35	0.1				

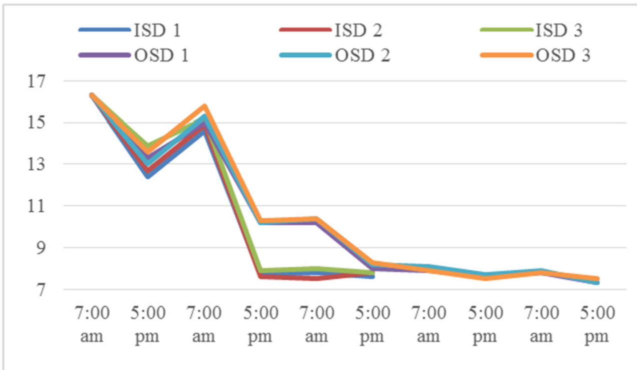

Fig. 4. Coffee weight with respect to time.

TABLE IV. T-TEST OF WEIGHT OF THE CORN

Dryer	Mean	SD	Diff.	t	P-value	Interpretation
ISD	11.40	0.1	0.23	2.21	0.09	No sig.
OSD	11.17	0.14				

D. Drying Duration and Condensation Phenomena

The drying time is determined by the time it took for the ideal moisture content to be achieved. Table V and Figures 4-5 show the drying duration of coffee and corn under ISD and OSD. The difference in drying time between coffee and corn, 20h for coffee and 6h for corn, is significant for farmers looking to save revenue on labor and other expenses. Condensation in the ISD's floor was eliminated due to the mesh that acts as a drying surface inside the ISD. Condensation happens when the temperature of the crops or the dryer's surfaces falls below the drying air's moisture content. Without the mesh wire, the temperature of the crops will be higher at the top than at the bottom because the top layer of the crops is subjected to solar radiation and the temperature is enhanced by heat absorption. Incoming air from the SAH, on the other hand, reaches the bottom portion of the crops through the mesh wire and progressively dries the crops at the bottom. Another strategy to avoid condensation from forming is to increase the mixing rate after sunrise to transport the warm top layer of the crops to the bottom layer.

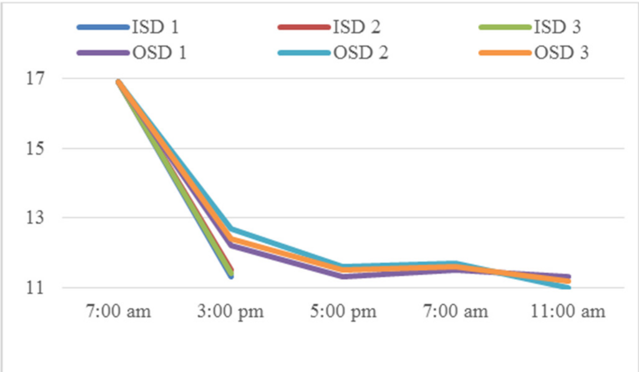

Fig. 5. Corn weight with respect to time.

TABLE V. DRYING DURATION OF COFFEE BEANS AND CORN

Products	Moisture content	Drying duration (hours)	
	Dried product	ISD	OSD
Coffee	12.0%	27	47
Corn	13.0%	8	14

IV. CONCLUSION

Due to the erratic rainfall, drying crops, particularly corn and coffee, is difficult in the Philippines, even during the dry season. To prevent such a situation, some farmers trade their products as soon as they are harvested (wet crops). However, because the market for freshly picked corn and coffee beans has poor farm gate prices, most farmers are drying their crops on roads and walkways to increase their income, even though this results in unclean and hazardous quality. The proposed ISD can help with these issues since it preserves the crops from damage, high yield losses due to pests, prolonged drying times, and uncertain weather changes. The dryer is easy to transfer, fix, and set up in a new area. Since it is made out of plastic and only has a few mechanical components, its simple design is easy to maneuver and maintain. The results of the trials reveal that 3 batches of 16.3kg coffee may be dried to an ideal moisture content of 12% on the third day or an exact period of 27h of drying. However, drying the same amount of coffee in the open sun takes 5 days or 47 hours. In the case of corn, the results demonstrate that 13% moisture content can be achieved in less than a day, or 8h, whereas it must be dried for a second day, or an equivalent of 14h, in the open sun. Based on the data acquired throughout the testing, the drying time will considerably impact the weight of the crops in a way. The ventilators are turned off after 5 p.m., and the crops are retrieved from the dryers since this experiment should be based on farmers' actual practice of OSD. Further study should concentrate on integrating solar energy storage [11, 12] on the solar air heater to continuously heat the air entering the drying chamber, even during the night or when there is no sunlight. Additionally, automatic control and notification of the condition of the dryer and dried products are necessary to avoid over-drying, which results in excessive moisture loss.

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