Experimental Evaluation of a Natural Indirect Solar-Biomass Dryer with Automated Single Axis Solar Tracking System for Urban Dwellers

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ABSTRACT

Many crops are seasonal in nature around the world; for this reason, there is a sustained need in finding better ways of processing and preserving them – to avail them in times of their lack and to ensure for their market sustainability. In this work, a natural indirect solar-biomass dryer with automated single axis solar tracking system was constructed and evaluated at the Ahmadu Bello University, Zaria using the meteorological conditions of Zaria, Nigeria. Apart from designing a system that can be used at both fair and adverse weather conditions, to help maximize the solar energy collected on the flat plate collector (FPC) without discomforting the user who may also want to attend to other needs, an automated single axis solar tracking system was incorporated to the flat plate collector (FPC) to help track the sun. The performance of the solar dryer in terms of the moisture content, drying rate, collector efficiency and drying efficiency was evaluated when the FPC was made to track the sun automatically; 36.67%, 1.73×10^{-4} (kg/s), 68.68% and 23.12% were respectively recorded for the moisture content, drying rate, collector and drying efficiencies for this test. By automatically tracking the sun with the FPC, the solar dryer's performance was also improved upon over the fixed FPC system. The experimental test on the solar-biomass system to evaluate the extent the individual dryer systems can remove moisture from the tomato product, the biomass drying system was found to be of highest performance, followed by the solar-biomass and lastly the solar system. For the hours of drying, a moisture 0.60 kg, 0.73 kg and 0.93 kg was respectively extracted by the solar, solar-biomass and biomass drying systems from the product.

Keywords: *Solar-biomass, automated axis, tracking system, solar dryer*

1.0 INTRODUCTION

The activities of post-harvesting of farm produce especially drying is one major crop preservation method employed to see that crops are preserved with little or no nutritional value loss and made valuable in times of scarcity (control market). For instance, Reddy *et al*. (2018) reiterated the need for drying by ascertaining that it avails seasonal food throughout the year to meet the thirst of food lovers [1]. Since the availability of most crops like fruits and vegetables around the world is seasonal [2], there is therefore a need to preserve them in times of abundance for use in times of scarcity; this however is not always pursued.

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In many countries across the world especially the developing countries, there is improper handling of perishable agricultural produce leading to wastages. In agreement with this fact, about 50% of produced fruits and vegetables are lost after harvest [2]. Toğrul and Pehlivan (2004) also emphasized that the estimations of these losses are generally cited to be within the region of 40%, while under very adverse conditions, can be nearly as high as 80 percentages [3].

Drying is reported to be one of the oldest methods of preserving food practiced by humans and known to extend the shelf life of the food product [1]. It was also reported in [4-5] the benefits of drying by enumerating that it reduces transportation cost by lowering the weight and volume, packing size, storage space of the product.

The open sun drying is the oldest means of drying but due to some limitations like; it requires a large area of land, which is not always available, its drying could be uneven, the method involves the high cost of labor; and low quality of products due to attack by dust, birds, insects and other foreign objects [6-7]. The limitations of this method were also stressed by Madhlopa *et al*. (2002) to include exposure of the foodstuff to rain and dust, uncontrolled drying, exposure to direct sunlight which is undesirable for some foodstuffs, infestation by insects and attack by animals [8].

In finding the remedy with challenges associated with open sun drying, solar drying evolved which protects the food from contamination and weather conditions while retaining the nutritional values of the food [9]. While renewable energy has been having a growing awareness in extending technology to the farmers in developing countries to increase their productivity, the solar thermal technology especially avails more measures in saving energy in the agricultural application for increasing yield [10]. Bolaji and Olalusi (2008) reported that this source of energy is preferred over other alternative sources of energy because it is in abundance, inexhaustible (renewable), and non-polluting [11]. Though the use of this energy for open drying of crops is however faced with some inherent problems. but the invention of solar dryers is therefore to reduce wastages of agricultural food materials and to significantly improve the quality of the dried products in comparison with the traditional open sun drying method [3, 12-13]. The uses of solar dryers are also reported to be cheaper and more practical as compared to mechanical dryers.

Solar dryers though have proven to be more reliable and advantageous than open sun drying, they also have some limitations, like problems faced when being used during adverse weather conditions and the night times without auxiliary heat backups. Auxiliary heat backups serve as an additional heat source to reducing drying time, increase efficiency, and ensure continuous drying [14-16]. During cloudy days and after sunset, a biomass heat source is reported to be used as heat backups because it is a cheap alternative and/or supplementary heat source for drying [17]. While the solar dryer serves as the primary dryer, the biomass dryer system acts as an auxiliary heat backup, that provides the needed energy supplied to the dryer when solar energy supply is low or completely absent, this sustains the process with little or no hitches. Using solar –biomass hybrid system is better because, apart from the cost of using biomass alone to dry, this method of drying is also known to reduce the quality of products in terms of nutrients when compared with solar drying [18]. A solar-biomass hybrid system which is a combination of the two drying systems meant to checkmate the problem associated with solar drying (redundancy at adverse weather conditions) and biomass drying (low food quality). Since it is reported that drying done using solar dryers retain more nutrients [18].

Research on the use of this hybrid system for drying has received adequate attention of the research community, where so much research was done to investigate the system efficiency and reliability, Tarigan and Tekasakul (2005) designed a mixed-mode natural convection solar dryer which they integrated with a biomass burner for drying agricultural product [19]. The drying efficiency of the solar component with and without heat storage was respectively reported to be 23% and 40%. They reiterated that the combined unit had an acceptable thermal efficiency and uniform product drying across the tray. Dhanushkodi *et al*. (2015) investigated a solar-biomass hybrid system for cashew (*anacardium occidentale*) drying [20]. They reported the system as having 3.6 g/h moisture removal rate with 55% average collector efficiency. They also observed that the system saved 66% of drying time against open sun drying. Okoroigwe *et al*. (2013) designed a combined solar and biomass cabinet dryer for yam chip (*dioscorea cayenensis*), drying with a maximum tray temperature of 53 °C and 0.0142 kg/h drying rate [21]. The drying rate obtained in the individual solar drying and biomass drying was 0.00732 kg/h and 0.0032kg/h respectively. Prasad and Vijay (2005) constructed an integral type of natural convection solar dryer incorporated with a biomass burner [22]. They evaluated the performance of the dryer by drying ginger (*zingiber officinale*), turmeric (*curcuma longa*), and *guduchi* (*tinospora cordifolia*) during the summer season in Delhi. Their results showed that during the load test for ginger, 18 kg of the fresh product with an initial moisture content of 319.74% was dried to a final moisture content of 11.8% within 33 hours. Also, the moisture content of turmeric and *guduchi* was reduced from 358.96 to 88% and 257.45 to 9.67% during 36 and 48 hours of drying, respectively.

Rigit *et al*. (2013) reported that a natural convection indirect solar dryer with backup biomass burner for small scale pepper berry farmers was designed and implemented [23]. They reported that the additional biomass backup heater shortened the drying duration of pepper berries from 5-7 days to a single day with continuous drying. Geramitchioski *et al*. (2011) constructed a mobile hybrid solar-biomass dryer for drying of vegetables and fruits with capacity that was suitable for use in single farm and small cooperatives [24]. They dried some apples at a temperature between 60-70ºC. They reported that the final moisture content of the apples was 20% with an average drying rate of 8 sunshine hours. Not only hybrid solar-biomass system developed in an attempt to address this problem, but so many inventions are also made in which many have yielded a very good result that improves the drying process like designing, constructing and testing the performance of a mixed-mode solar dryer for food preservation [25]. In the dryer, heated air from a separate solar collector is passed through a grain bed, and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls and roof. Results obtained from the test showed that the temperatures inside the dryer and solar collectors were much higher than the ambient temperature during most hours of the day-light. The temperature rise inside the drying cabinet was up to 74% for about three hours immediately after 12.00 noon. Abubakar *et al*. (2018) developed and tested a mixed-mode solar crop dryer with and without thermal storage materials under the same meteorological conditions of Zaria, Nigeria [26]. It was observed that the average drying rates, collector efficiencies, and drying efficiencies of the solar crop dryers with and without thermal storage for June and August 2016 test period were 2.71×10^{-5} kg/s and 2.35×10^{-5} kg/s, 67.25% and 40.10%, 28.75%, and 24.20% respectively. For the experimental results, the efficiency of the dryer with the storage materials is enhanced by about 13% due to the thermal storage used. Also, the *p*-values obtained showed that there was no significant difference between the drying rates of the yam slices on different positions of the trays. Forson *et al*. (2007) designed and tested a mixed-mode natural convection solar crop dryer; used for the drying of cassava and other crops in an enclosed structure [27]. A drying time of 30 to 36 hours was assumed for the anticipated test location (Kumasi: 6.71ºN, 1.61ºW) with an expected average solar irradiance of 400 W/m² and the ambient temperature of 25ºC and relative humidity of 77.8%. The dryer when tested under a fully designed load of average ambient conditions of 28.2ºC and 72.1% relative humidity with solar irradiance of 340.4 W/m², a drying time of 35.5 hours, and drying efficiency of 12.3% were obtained.

Researchers note that there is a possibility of increasing the amount of solar energy trap from the sun, that is by the users of the solar tracking system, whether automated or manual the efficiency of solar dryers can be improved significantly. It was reported in [28-29] that reflectors can be used to improve the efficiency and amount energy trap by the flat plate collector, also the amount of solar energy trap from the sun by flat plate collector can be improved by tracking the sun, as such extra energy can be harnessed. It is reported that maximum solar energy can be received all day long when the solar energy collector's surface is perpendicularly placed to the solar rays [30]. The main role of a tracking system is therefore to collect solar energy for the longest period of the day; thus, solar tracking ensures that the maximum amount of sunlight strikes the collectors throughout the day [31]. It has also been estimated that the use of a tracking system, over a fixed system, can increase the power output by 30–60% [32]. Tracking can be achieved manually or by automation [31]. The manual tracking system is cheaper to install but it needs the attention of a man. Even though the automated tracker can add to the initial cost of the system [32], it was employed in this work to help create time for the user to attend to other pressing matters since the system can operate itself. Because of the extra cost incurred in the installation of the automated system, the dryer system may be assumed to be meant for urban farmers (dwellers) who are oftentimes considered richer because of their involvement in other businesses that bring them profit.

In previous works conducted and reviewed, there have been little or no attempts by the researchers in trying to maximize the solar energy collected on the FPC by the automation process before going ahead to include the backup heater. This work, therefore, presents a solar-biomass dryer with the automation of the FPC to help maximize the solar energy collected on the FPC; as such, without any attendance by the farmer (user).

2.0 MATERIALS AND METHODS

2.1 Description of the Dryer System

The system is made of two sections – the solar and the biomass drying sections. It consists basically of the flat plate collector, the drying chamber and the biomass combustion chamber as shown in Figure 1.

Flat Plate Collector (FPC)

This is a rectangular metal frame box overlaid at the bottom first with a plywood, then with an aluminum absorber plate with sawdust sandwiched in between them and covered at the top with a transparent glass cover. The FPC provides the platform where the solar energy is harvested. It heats up the air passed into the dryer. It has the following parts:

Absorber plate:

Treated black material with high absorptance and low long wave emittance are the most preferred absorber material [33]. The aluminum sheet metal was used as the absorber plate. The sheet metal was made of length 797 mm, width 531 mm with an approximate thickness of 0.8 mm.

Glazing or glass cover:

This is the top cover of a solar collector. Prasad *et al.* (2010) reported that glass has been the principal material used to glaze solar collectors due to the fact that it has highly desirable property, transmitting as much as 90% of the incoming short-wave radiation energy while virtually avoiding the outward escape by transmission of none of the long wave radiation emitted by the flat plate [34]. The transparent glass was also selected as the glazing material for this work. It was made of length 797 mm, width 531 mm and thickness 4 mm.

Insulation:

This minimizes the heat loss to the surrounding. The selection of insulating material is based on its cost, availability, effectiveness and durability. The sawdust was used for this work because it has low thermal conductivity, economically cheap and readily available. The sawdust was sandwiched in between the bottom of the collector and the absorber plate.

Reflectors:
The back silvered glass was used for this work since it has excellent specular reflectance and excellent durability. The approximate dimension of 797 mm × 265.5 mm was used on both mirrors such as to make it serve as a cover to the solar collector plate and positioned facing east and west of the FPC. The angular positions of the reflectors placed east and west of the FPC were 40° and 80° respectively relative to the horizontal plane [31].

Connecting duct:
This serves to deliver the heated air from the collector plate into the drying chamber. It was made of 2 mm mild steel and diameter 53.1 mm.

Drying chamber:
This is an enclosed structure where drying takes place. It is made with mild steel frame and plywood body screwed in place with a protruding chimney on top. It consists of the following parts:

Casing or dryer's body:
Galvanized iron, wood, fiber sheet, steel and aluminum, etc. are some commonly used casing materials. The casing is made of plywood of about 10 mm thickness with 753 mm × 531 mm dimension.

Trays:
Dryer trays are made to have air gaps for air to gain access through to the product being dried. The wire mesh was used for making of the trays in this work. The wire mesh was made to the dimensions of 753 mm × 531 mm.

Chimney:
This serves as an air vent to the drying chamber. A cylindrically shaped mild steel of 2 mm thickness was used to make the chimney. It is made of diameter 53.1 mm and height 407 mm.

Support frame:
This is made to support the drying chamber. The support frame is made of mild steel of 3 mm thickness. The support frame has a total height of 1000 mm from the ground.

Biomass combustion chamber:
This is the chamber for burning the fuel (charcoal). It is made up of the following parts:

Combustion chamber:
The combustion chamber is made of 2 mm mild steel; with a diameter of 375 mm and height of 593 mm.

Grate:
The grate is made of 2 mm mild steel with a diameter of 375 mm to fit into the combustion chamber. 10 mm holes were evenly bored on the grate to allow for ash dropping.

Door:
The combustion chamber's door cover is made with 2 mm mild steel to a dimension of 120 mm × 120 mm

A schematic diagram of the solar-biomass dryer system is shown in Figure 1.

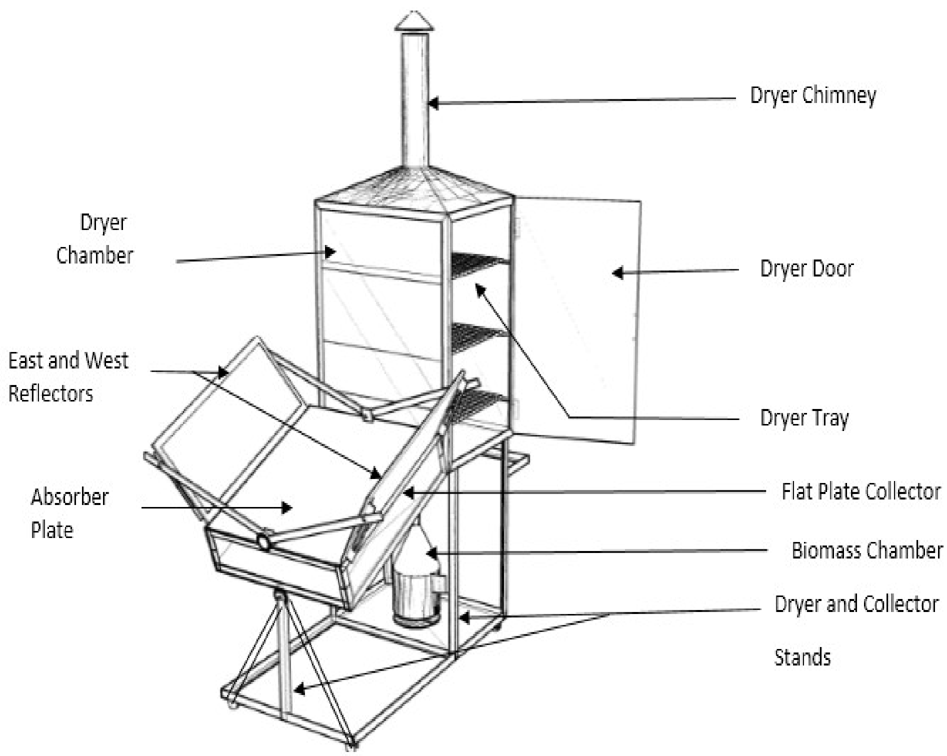


Figure 1: A schematic diagram of the dryer system

2.2 Working Principle of the Dryer System

The FPC is opened at one end for ambient air entrance and the other end linked to the drying chamber by a circular pipe whose diameter is about one-ninth the size of the FPC that is opened to the ambient air. The collector is normally energized by the sun's rays entering through the glazing cover. Boosted by the reflectors, the glazing cover traps the heat from the sun by converting high frequency, low wavelength radiations into low frequency, high wavelength radiations (greenhouse). The trapping of the sun rays is enhanced by the inner surface of the collector made of aluminum sheet painted black; the trapped energy then heats up the air inside the collector. The greenhouse effect achieved within the collector drive the air current from the inlet to the outlet of the collector setting a thermo-siphoning effect creating an updraft of the heated air into the drying chamber. The heated air is then circulated by natural convection, transferring energy to the crop in the drying chamber where it evaporates and removes water from the crops and finally expelled through the chimney depending on the humidity factor of the air. The exit of air from the collector plate creates a vacuum in the system aiding natural convection current process to be regenerated thereby causing the whole process to undergo a repetition as the dryer is placed in the path of airflow until the crop is brought to drying or the desired moisture content.

The biomass burner is used for supplying heat for drying at periods of low or zero solar radiation. The charcoal burner has a perforated grate which allow for ash drop into the lower tray and its wall aligned with clay refractory material to help reduce heat loss by conduction. The system is also incorporated with a steel gas to gas heat exchanger which ensures that clean air reaches the products. As the charcoal fuel is lit up into burning by natural draft, the hot gases moves into the top of the burner which is conically shaped to ease direct the hot gases through the heat exchanger into a pipe which then conveys them over the trays in the drying chamber picking up moisture from the crop and then finally expelled through the chimney. This process undergoes a repetition until the crop is dried to the desired moisture content.

2.3 Conditions/Assumptions for the Design of the Solar Dryer

The parameters as shown in Table 1 were considered in the design of the dryer while Table 2 shows the summary of the dimension of the constructed drier.

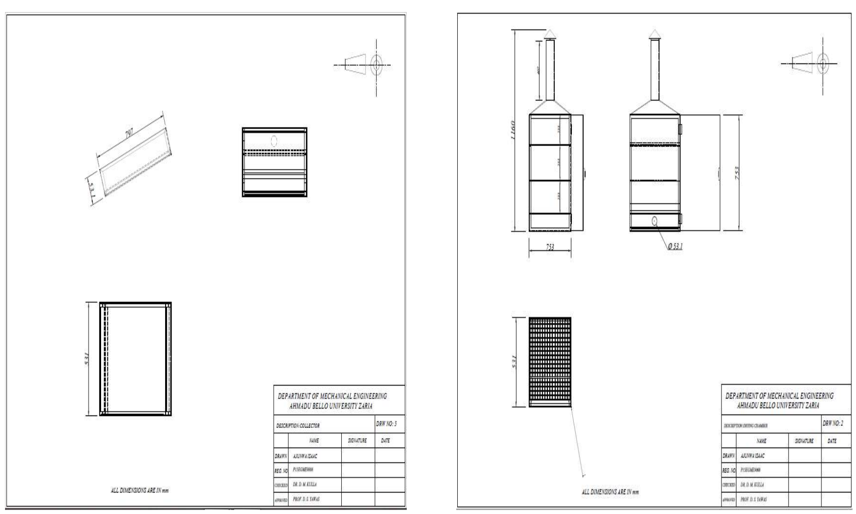
Table 1: Design conditions and assumptions

Items		Conditions/Assumptions
a.	Location	Zaria, Nigeria (Long. 07°38', Lat. 11°07')
b.	Ambient air temperature (TRNSYS 16)	25.5^{o}C
c.	Maximum allowable [35]	70^{o}C
d.	Sunshine hours [26]	5 hours (drying time)
e.	Wind speed (TRNSYS 16)	2.43 m/s
f.	Initial moisture content of tomatoes	94%
g.	Final moisture content of tomatoes	10%
h.	Emissivity of glass cover [36]	0.88
i.	Emissivity of absorber plate [36]	0.95
j.	Collector efficiency [37]	30-50%
k.	Monthly average total radiation (TRNSYS 16)	16.60 MJ/m^{2}day
l.	Absorber thickness [38]	0.8-1.0 mm
m.	Glazing thickness [38]	4-5 mm

Table 2: Summary of the dimensions of the constructed dryer

Parameter		Computed dimensions
a.	Length of collector (L_c)	0.797 m
b.	Width of collector (W_c)	0.531 m
c.	Area of collector (A_c)	0.423 m^2
d.	Drying chamber length (L_d)	0.753 m
e.	Drying chamber width (W_d)	0.531 m
f.	Drying chamber volume (V_d)	0.012 m^3
g.	Chimney height (H_{ch})	0.407 m
h.	Chimney diameter (D_{ch})	0.0531 m
i.	Combustion chamber width (W_{cc})	0.375 m
j.	Combustion chamber height (H_{cc})	0.593 m

The sectional diagrams of the solar-biomass dryer parts are shown in Figure 2.



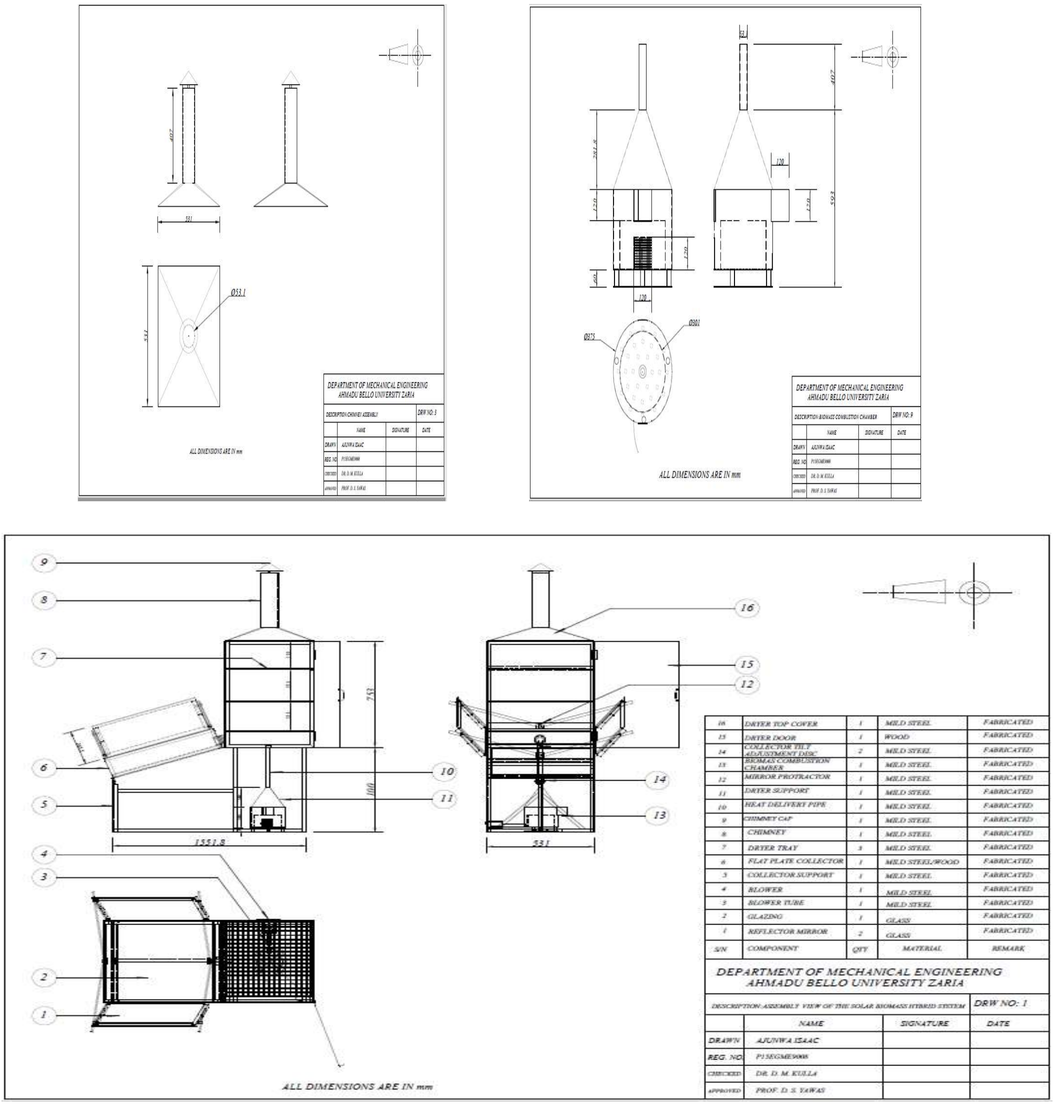


Figure 2: Sectional diagrams of the solar-biomass dryer parts

2.4 Solar Collector Orientation

The flat plate solar collector should be tilted and oriented in such a way that it receives maximum solar radiation during the seasons of drying; and to allows for easy runoff of water and enhance air circulation. The best stationary orientation is due south in the northern hemisphere [39]. From the result of parametric optimization, the solar collector plate in this work was tilted at 20° [40], which approximately agrees with the findings of [41-42] who suggested latitude of the location plus 10 degrees as the optimum tilt angle of a collector plate for the place of the experiment is 11.2° (latitude for Zaria, Nigeria).

2.5 Motion of the Solar Collector Plate

The solar FPC was designed in such a way that it can be operated at fixed point and in an automated motion. To operate it automatically, the link connecting the FPC and the automated mechanism (rack and pinion of the DC motor) was bolted while for a fixed point operation, the bolt was loosened off the link. To control the DC motor at specified time (15°), the circuit was made comprising majorly of the: real time clock (RTC) module, microcontroller, tactile switches, relay modules and power supply using battery. The circuit diagram is as shown Figure 3.

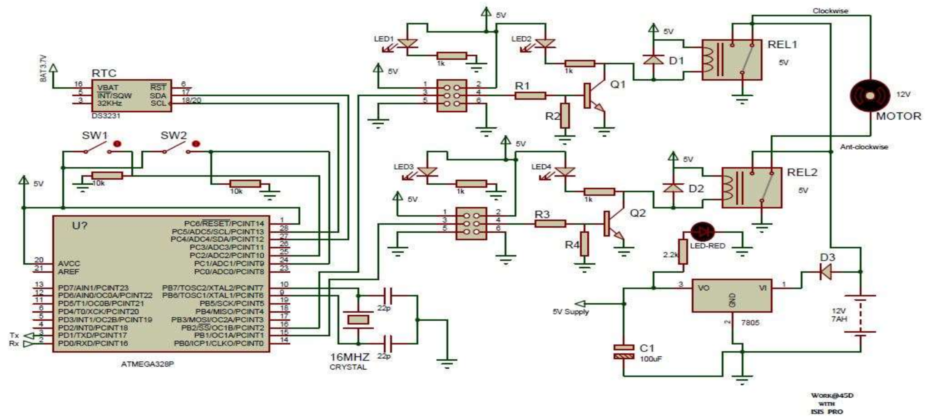


Figure 3: Circuit diagram for the control of a dc motor at specific angle using RTC and microcontroller

2.6 Structure of the Auto-control System

The structure of the auto-control system is subdivided into the following units: power supply unit, microcontroller unit, timer unit, switching unit and the coding system.

Power supply unit: The circuit have a rechargeable sealed lead acid battery of 12 V, 7 Ah rating to power the system (DC motor). If down, the battery was recharged by a 100 W, 5.71 A and 17.5 V rating solar panel, through its 24 V, 20 A charge controller. The power system has a LED placed along the path of the supply to indicate its state whether ON or OFF. A diode is also put in series with its positive terminal to prevent flow of current to the motor when programming the microcontroller. Most parts of the circuit, however, require a maximum of 5 V to operate optimally, for this reason the 12 V is regulated using *LM7805*. The *LM7805* is a linear voltage regulator that takes in voltages from 7-25 V and delivers the output of approximately 1 A, 5 V. Across its output, a 100 µF capacitor is placed to smoothen the regulated voltage, thereby removing the ripples. The excess voltage drop at the regulator is deducted as:

$$V_{\text{drop}} = V_{\text{supply}} - V_{\text{out}} \tag{1}$$

Noting that $V_{\text{supply}} = 12$ V, $V_{\text{out}} = 5$ V and $I = 1$ A, then, the power dissipated can be determined as:

$$P_{\text{dis}} = V_{\text{drop}} \times I \tag{2}$$

or

$$P_{\text{dis}} = (12 - 5) \times 1 = 7 \text{ W}$$

This power is dissipated as heat; hence an appropriate heat sink was used for efficient performance. The regulated 5 V was then supplied to all parts of the circuit that require 5 V to operate.

Microcontroller unit: The microcontroller used is one of the members of the *AVR Atmega* series, *ATMEGA328P*. It is a 28 pin dual in-line package (DIP) IC that functions similar to other AVR series like atmega32, atmega128, attiny85, etc. The IC has internal clock, but for better clocking, an external 16 MHz crystal oscillator was attached at the pin 9 and 10 as described in the datasheet. The *AVR Dragon* programmer was used to upload the HEX file into the microcontroller. Other programmers capable of been used for this purpose are the *STK500*, FTDI module, *Arduino* as ISP, etc. The IC is programmed through the pins 1, 2 and 3 which are the Reset, Tx and Rx, respectively.

Timer unit: In order to keep timing for the circuit, the internal timer registers could be activated using the code; but this has sets back as the time resets every moment power to the microcontroller is interrupted. The timer used is a RTC module based on the *DS3231* timer IC, the module is equipped with a 3 V *CR2032* cell coin battery that enables the RTC to keep time even when supply to the Microcontroller is cut off.

Switching unit: This unit comprises of two channels, 5 V relay modules and two tactile switches. The microcontroller was programmed to control the relays at the appropriate timing. Also, for manual operation in the case of trouble-shooting, the tactile switches were used to turn the relays ON or OFF. The relays in turn connects the motor's terminals in an orientation that makes it move in clock-wise or anti-clockwise direction. The motor was powered directly by the 12 V battery whereas the relays were powered with the regulated 5 V.

Coding: The program was written using C^{++} language as it commonly used to program AVR series. The code issues command to the microcontroller to read the timing from the RTC and if it corresponds to the set time, a pulse width modulated (PWM) signal was sent to the output of pin 15 and 16 of the *ATMEGA328P*. Similarly, it reads the input at the analog pins A1 and A2 where the switches are connected. When a switch was pressed, an input signal was sensed at the connected pin and the microcontroller sends a PWM signal to the appropriate output pin. The PWM signal was used to switch the corresponding relay for a specified time. Pins 16 and 15 were used to control Relays 1 and 2, respectively.

2.7 FPC Orientation

The flow chart describing the orientation of the flat plate collector (FPC) of the solar drier system is shown in Figure 4. Note that the collector was configured to step by itself with RTC defined time (motion of 15°) for every 1 h movement of the sun. A programmed 4.0 Nm and 8.0 rpm DC motor was incorporated unto a constructed mechanism having 15° rack and pinion to ease hitching movement of the motor. This arrangement was in-turn coupled directly beneath the solar FPC so that as the motor drives the mechanism, the collector plate is moved through the same angle.

The DC motor was controlled by a program language written in C^{++} in such a way that the solar collector plate is positioned in three steps (45°) from its horizontal position facing eastward (this is its default state by 9.00 am). During the period of drying, 9.00 am to 5.00 pm, the solar collector plate moves a step, 15°, for every one hour toward the west. Before a motion is recorded, the microcontroller checks the RTC timer, if the time corresponds to the program (defined) time, the motor rotates by the corresponding time (motion of 15°); if not, the microcontroller waits and keep checking the programed (defined) time from the RTC for correspondence and order of the circuit for response accordingly.

The RTC was assigned with specific defined times of the day: 10.00 am, 11.00 am, 12.00 pm, 1.00 pm, 2.00 pm, 3.00 pm and 4.00 pm when the last motion was observed. Therefore, by 12.00 pm, according to the programmed time, the FPC is horizontally positioned facing the sun which is directly over-head at this time. By 5.00 pm, at the time the microcontroller accepts time of correspondence from the RTC and orders the circuit, the collector plate instead at a steady wind movement moves backward to its original or default state waiting for drying to commence the next day. The motion is automatically repeated as the circuit is powered. With this, drying is carried out from 9.00 am to 5.00 pm by tracking the sun with the automatic movement of the FPC. The pictorial views with the automation of the FPC facing the sun at noon time, before noon time and after noon time are shown in Figure 5. The code for the program written to automatically operate the collector plate is given in Appendix A.

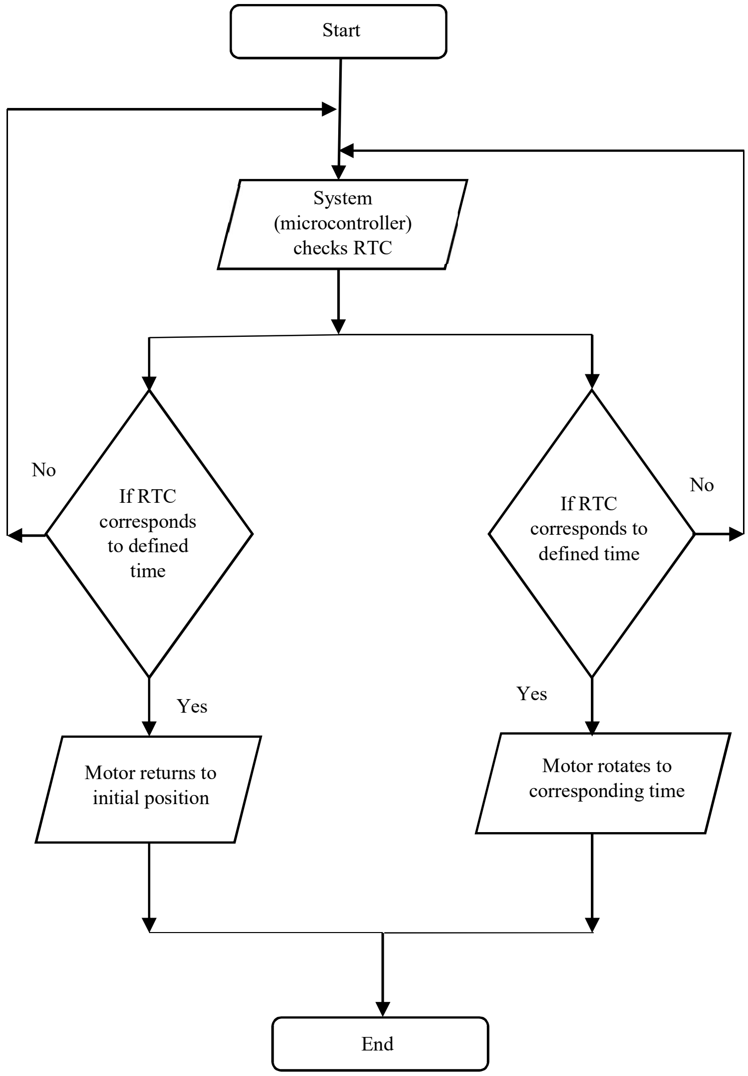


Figure 4: The flow chart of the orientation of the FPC

(a) (b) (c)

Figure 5: Pictorial (real) views of the automated flat plate collector (FPC) (a) facing the sun at noon time (b) facing east before noon time (c) facing west after noon time

3.0 EXPERIMENTATION OF THE SYSTEM

3.1 Instrumentation of the System Dryer

The *SL-100* Solarimeter which measures the combined direct and diffuse solar radiation of the sun was used to measure the solar radiation on the glazing surface of the collector. The equipment displays at an accuracy of ± 5 W/m^2 with measuring range from 1 to 1300 W/m^2 and an energetic exposure from 1 to 500 kWh/m^2. Thermocouple wire and digital thermometer: the ambient air temperatures, collector outlet air temperature and the drying chamber temperature were all measured using copper/constantan thermocouple wires and a digital *Kane-May 340* thermocouple device that measures temperature either in Celsius or Fahrenheit. The equipment has a measuring range from -50°C to 1300°C (-58°F to 1999°F) and a resolution of 1°C. The digital *Camry* weighing scale with an accuracy of 0.0001g was used to measure the weight loss of the tomato slices. The wind speed of the surrounding ambient air was measured using the *EL-3* aero vane digital anemometer which has a measuring range from 0 – 30 m/s.

3.2 Testing the Dryer

Experiments were conducted on the solar-biomass dryer under the meteorological conditions of Zaria, Nigeria, Latitude 11° 7' 48" and Longitude 07° 41' 8" with average recorded solar insolation and wind speed as 530 W/m^2 and 2.3 m/s, respectively. The moisture removal and thermal analysis which are the basic standard procedures for evaluating solar dryer performances as recommended by Leon *et al.* (2002) were also used in evaluating the dryer [43]. Each of the experiments of solar drying and biomass drying systems were carried out from 9.00 am to 5.00 pm, with that of the biomass conducted on a cloudy day. The solar-biomass drying system was carried out at succession; beginning with the biomass drying from the morning hours of 9.00 to 11.00 am and concluding with same method in the evening hours of less insolation, while the solar drying process was conducted from 11.00 am to 3.00 pm, the period of better solar insulation. Each test took eight hours to have a time base for comparison. Before switching to a method, the other was shaded to avoid energy invasion from such into the dryer [44]. In its procedure of testing, the solar dryer was exposed to solar radiation and loaded with 2.0 kg of tomato slices of about average thickness of 5-10 mm on each of the three trays. Energized air from the FPC or from the biomass burner chamber is siphoned into the drying chamber where it is circulated transferring energy to the crop removing water from it and finally expelled through the chimney. The process undergoes a repetition until the crop is dried to the desired moisture content. During this process, the weight of the tomato slices on each tray was measured at hourly intervals. Hourly temperature of the dryer, ambient air temperature, collector air outlet temperature, solar insolation, as well as the wind speed were also measured as it is in line with ASHRAE/ANSI 93-2003 standard for evaluating the thermal performance of a solar collector [45]. This method was also used by Nabnean *et al.* (2016) [46]. The performance of the system was evaluated using the hourly moisture loss, drying rate, collector and system drying efficiencies. The amount of moisture removed was compared for the solar, biomass and solar-biomass drying systems while the moisture content, drying rate, collector and drying efficiencies parameters of the automated tracking mode was compared with same parameters of the non-tracking mode published earlier [31].

3.3 Evaluation of the Dryer

The relevant parameters were evaluated using the equations as described in the following paragraphs.

Percentage moisture content, m_{wb} on wet basis was calculated as [47]:

$$m_{\mathrm{wb}} = \frac{w_w - w_d}{w_w} \times 100\% \quad (3)$$

Where

w_w	:	weight of wet product
w_d	:	weight of dried product

Average drying rate, m_{dr} was calculated as [48]:

$$m_{\mathrm{dr}} = \frac{M_{\mathrm{w}}}{t_{\mathrm{d}}} \tag{4}$$

Where

M_w	:	mass of water evaporated from the product
t_d	:	drying time

Solar collector efficiency, η_c was calculated from [27]:

$$\eta_{\mathrm{c}} = \frac{\dot{m}_{\mathrm{a}} C_{\mathrm{p}} (T_{\mathrm{o}} - T_{\mathrm{a}})}{A_{\mathrm{c}} I_{\mathrm{T}}} \tag{5}$$

Where

I_T	:	total solar radiation incident on the surface
T_a	:	ambient air temperature
T_o	:	temperature of outgoing air from the collector
$\dot{m}_a$	:	mass flow rate of air

Dryer efficiency, η_d was calculated as [27]:

$$\eta_{\mathrm{d}} = \frac{M_{\mathrm{w}} L_{\mathrm{v}}}{I_{\mathrm{T}} A_{\mathrm{c}} t} \tag{6}$$

Where

M_w	:	mass of water evaporated
L_v	:	latent heat of vaporization of water
t	:	drying time
A_c	:	collector area

4.0 RESULTS AND DISCUSSION

4.1 Automated Tracking System of the FPC

Figures 6 to 9 respectively shows the variation in graphs of the moisture content (%), the drying rate (kg/s), the collector efficiency (%) and the drying efficiency (%) of the dryer for the experimental results for the automated tracking system of the FPC.

Figure 6 shows the variation of experimental result of moisture content for the automated tracking system. From the figure, it can be observed that the highest hourly average moisture content of 5.61% was recorded between the hours of 10.00 am and 12.00 noon due to an increase in moisture loss from the wet product. The hours of 1.00 pm and 3.00 pm had an average hourly moisture content of 3.65% with 4.85% recorded between 4.00 and 5.00 pm. The average hourly moisture content for the drying time was 4.58% while 36.67% was the total moisture for the entire drying time. In comparison with the test of the same dryer with fixed solar collector plate reported earlier in [31], a total moisture content of 31.99% was recorded for the 8 hours of drying; signifying that the automated tracking mode showed an improvement of 4.68% over the fixed mode system.

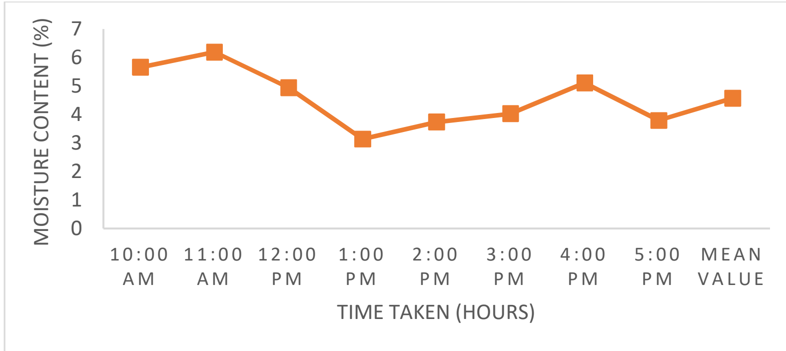


Figure 6: Variation of experimental *moisture content* and time taken

Figure 7 shows the experimental result of drying rate for the automated tracking systems. From the figure, it can be observed that the trend displayed by the graph of moisture content (Figure 6) is also true for the drying rate. An hourly average drying rate of 2.93×10^{-5} kg/s was recorded between the hours of 10.00 am and 12.00 pm due to high loss in moisture from the wet product and the harvest of the sun's energy by tracking. The hours of 1.00 pm and 3.00 pm recorded an average hourly drying rate of 9.82×10^{-6} kg/s with 1.81×10^{-5} kg/s recorded between 4.00 and 5.00 pm. The average hourly drying rate for the drying time was 2.16×10^{-5} kg/s while 1.73×10^{-4} kg/s was obtained as the total drying rate for the entire drying time. Again, in comparison with the test of the same dryer reported earlier in [31], having the solar collector plate fixed, a total drying rate of 1.54×10^{-4} kg/s was recorded for the entire hours of drying; the automated tracking mode therefore showed an improvement of 1.90×10^{-5} kg/s over the fixed mode system.

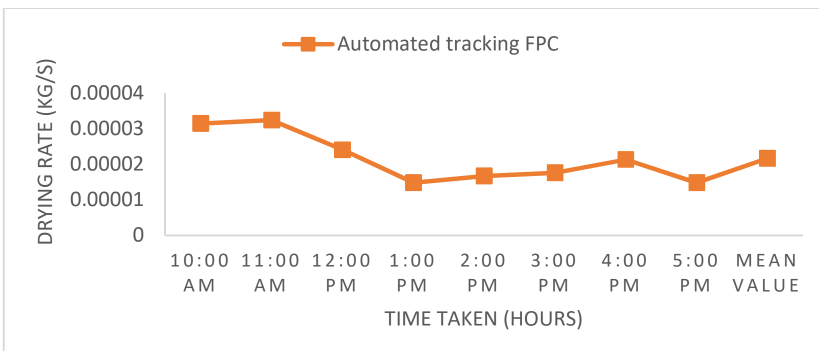


Figure 7: Variation of experimental *drying rate* and time taken

Figure 8 shows the experimental results of collector efficiency for the automated tracking systems. Intermittency in hourly solar insolation and air speed rates resulted to a collector efficiency curve quite different from that of the moisture content and the drying rate, these two factors being parameters in computing the collector efficiency. From Figure 9, it can be deduced that the hours of 10.00 and 11.00 am gave the least collector efficiency with an average value of 51.23%. Between the hours of 12.00 pm and 4.00 pm, the efficiency got improved recording an average value of 77.85%; which however reduced as the sun went down towards the evening hours with an efficiency of 68.68% recorded by 5.00 pm. The average collector efficiency for the drying time was 68.68%. In their report, Maiti *et al*. (2011) recorded a collector efficiency of 58.5% by the use of north-south reflectors [28]. The collector efficiency of 68.68% obtained in this work by using the east and west reflectors shows an improvement over that reported in [28]. An improvement of the collector efficiency was also reported for this mode system when compared with Potdukhe and Thombre (2008) who reported a collector efficiency of only 34% [49]. Also, in comparison with the test of the same dryer reported earlier in [31], having the solar collector plate fixed with an average collector efficiency of 65.17% recorded; the automated tracking mode therefore showed an improvement of 3.51% over the fixed mode system. The tracking of the morning and evening energy from the sun would have been responsible for this better result.

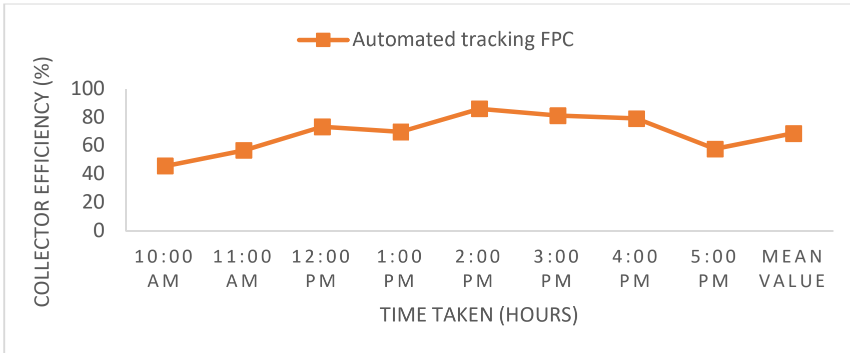


Figure 8: Variation of experimental *collector efficiency* and time taken

Figure 9 shows the experimental result of drying efficiency for the automated tracking systems. From the figure, it can be seen that an hourly high average drying efficiency of 30.08% was obtained in the morning hours of 10.00 and 12.00 noon. The hours of 1.00, 2.00 and 3.00 pm respectively recorded hourly drying efficiencies of 14.53%, 16.49% and 17.77%. Meanwhile, 22.98% was recorded as the average hourly drying efficiency between 4.00 and 5.00 pm. The average hourly drying efficiency for the drying time was 23.12% for the automated tracking system**.** Like the collector efficiency, the drying efficiency amidst other factors is also a function of solar insolation rate. Their graphs, however do vary, because in computing the drying efficiency, the weights of the product being dried is normally taken into consideration. When the total work done by the collector is not translated into the dryer (due to low flow rate) for uniform drying, it creates a trend variation in graphs of the efficiencies of the collector and the dryer. Potdukhe and Thombre (2008) reported a drying of 21% while the 23.12% obtained in this work shows an improvement of 2.12% [49]. The drying efficiency recorded here also agrees with that reported by Chan *et al.* (2015) who recorded an approximate equal drying efficiency of 23.6% within 5 hours of drying with a load of 104 kg but reported an improved drying efficiency of 35.7% with a load of 200 kg in 8 hours [50]; this is likely due to the recirculation technique employed in their design. The result here also showed an improvement over the drying efficiency range of 1.50 to 6.47%. Akoto *et al.* (2018) reported in their single-layer drying and an approximate equal drying efficiency range of 23.07 to 24.93% in the four-layer drying [51]. The test of the same dryer reported earlier in [31], having the solar collector plate fixed, gave an average drying efficiency of 21.33%. In comparison, the automated tracking mode showed an improvement of 1.79% over the fixed mode system.

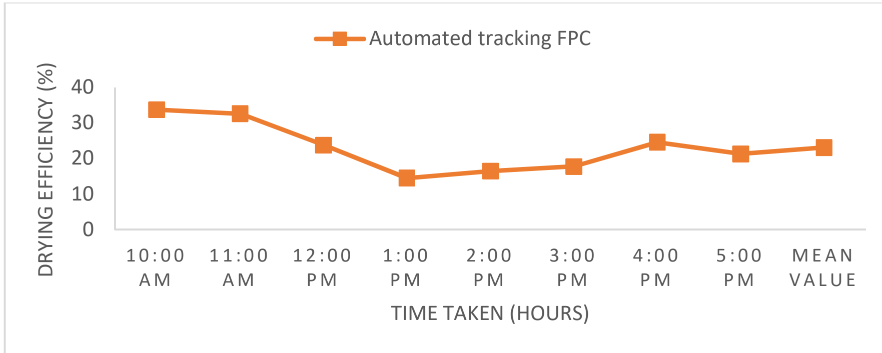


Figure 9: Variation of experimental *drying efficiency* and time taken

4.2 Solar, Solar-biomass and Biomass Dryer Systems

Figures 10 shows the variation of results of weight loss obtained from the tests of the solar, solar-biomass and biomass systems of drying.

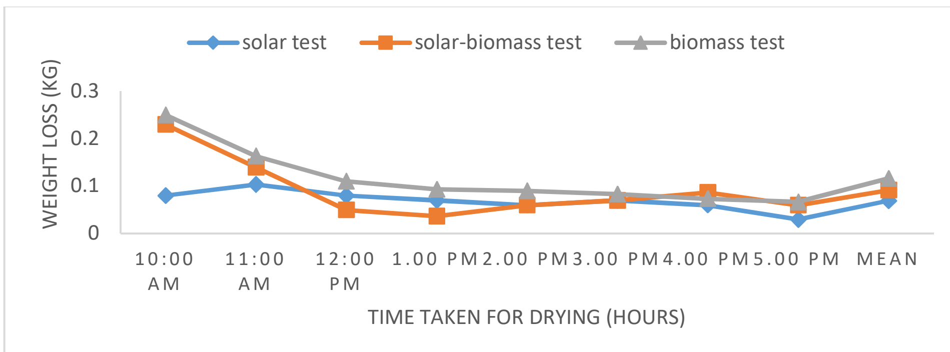


Figure 10: Variation of experimental weight loss with time for solar, solar-biomass and biomass drying systems

Figure 11 shows the variation of experimental weight loss with time for solar, solar-biomass and biomass drying systems. From the figure, for the period between 10.00 and 11.00 am, the weight loss from the product was observed to be higher with the solar-biomass and biomass drying systems as compared to the solar drying system due to the use of the biomass burner that supplied more heat than the solar insolation. An average weight of 0.09 kg, 0.19 kg and 0.21 kg was respectively lost from the solar, solar-biomass and biomass drying systems between 10.00 and 11.00 am. Between the hours of 12.00 – 3.00 pm, there was a reduction in the weight loss of the solar-biomass drying system, since the burner was put off and the use of the solar collector activated, the solar-biomass and the solar drying systems recorded lower weight loss as compare with the biomass drying system within this time. Within this period from 12.00 pm to 3.00 pm at one-hour interval, the moisture extracted from the product by the biomass drying system was 0.11 kg, 0.09 kg, 0.09 kg and 0.08 kg, respectively; 0.05 kg, 0.04 kg, 0.06 kg and 0.07 kg was however extracted using the solar-biomass system of drying and 0.08 kg, 0.07 kg, 0.06 kg and 0.07 kg extracted using the solar system within this same period of time. Again, as the commencement of the use of the biomass burner towards the evening falls, the moisture loss of the solar-biomass drying system was improved upon.

The average moisture loss value of 0.05 kg was recorded between 4.00 pm and 5.00 pm by the solar drying system, 0.074 kg was recorded by the solar-biomass system and 0.07 kg by the biomass. For the entire 8 hours of drying, a total moisture 0.60 kg, 0.73 kg and 0.93 kg was respectively extracted by the solar, solar-biomass and biomass drying systems from the product. The highest moisture loss was therefore recorded with the biomass system of drying, followed by the solar-biomass system and lastly the solar system. Due to the fact that higher moisture loss was recorded with the solar-biomass system with same hours of drying as compare with the solar drying system, it can be said that this observation also agrees with the reports in [14, 22-23] who stressed that solar dryers with backup heaters accelerate drying time. The results of the drying rates of the tests done on the solar-biomass, solar and biomass drying systems were reportedly at 0.0142 kg/h, 0.00732 kg/h and 0.0032 kg/h, respectively [21], thereby agreeing also to the fact that solar dryers with back heaters dry faster when compared to those without the backup heaters. They, however, asserted that the least drying rate with the biomass system of drying which is contrary to the observation here.

5.0 CONCLUSION

In conclusion, a solar-biomass dryer with the ability to automatically track the sun in a single axis was successfully designed, constructed and tested at the Ahmadu Bello University, Zaria using the meteorological weather conditions of Zaria, Nigeria. The test of dryer recorded 36.67% moisture content, 1.73×10^{-4} (kg/s) drying rate, 68.68%, collector efficiency and 23.12% drying efficiency. In comparison, a moisture content of 31.99%, drying rate of 1.54×10^{-4} kg/s, collector efficiency of 65.17% and a drying rate of 21.33% which was reported by Ajunwa *et al*. (2020) in testing the same dryer with the FPC fixed was improved upon [31]. By automatically tracking the sun, the moisture content, drying rate, collector and drying efficiencies were increased by 4.68%, 1.90×10^{-5} kg/s, 3.51% and 1.79%, respectively. In comparing the performance of the system in terms of weight loss of moisture of the solar, biomass and solar-biomass drying systems; the biomass drying system was found to be of highest performance, followed by the solar-biomass and lastly the solar system. For the drying hours, a moisture 0.60 kg, 0.73 kg and 0.93 kg was respectively extracted by the solar, solar-biomass and biomass drying systems from the product.

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Appendix A

Codes for the Control of the DC Motor in C^{++}

```
/** The code for the D.C auto-control system by I.A
reference: arduino.cc & examples in the public domain.**/
#include <Wire.h>
 #include "DS3231.h"
RTClib RTC;
int Rel_pin1 = 10; //relay 1 enable pin
int Rel_pin2 = 9; // relay 2 enable pin
int b1 = A1; //button 1 pin
int b2 = A2; //button 2 pin
int bs1;
int bs2;
void go15( );
void Switch1( );
void Switch2( );
void setup ( ) {
//assign the pin registers as Outputs and Inputs respectively
pinMode (Rel_pin1, OUTPUT);
pinMode (Rel_pin2, OUTPUT);
pinMode (b1, INPUT);
pinMode (b2, INPUT);
Serial.begin (9600); //baud rate for serial communication
Wire.begin( ); //initialize wire communication
}
void loop( )
{
DateTimenow = RTC.now( );
//print date and time to confirm if correct
Serial.print(now.year( ), DEC);
Serial.print('/');
Serial.print(now.month(), DEC);
Serial.print('/');
Serial.print(now.day(), DEC);
Serial.print(' ');
Serial.print(now.hour(), DEC);
Serial.print(':');
Serial.print(now.minute( ), DEC);
Serial.print(':');
Serial.print(now.second( ), DEC);
Serial.println( );
go15( );
Switch1( );
Switch2( );
}
void go15 () {
if (now.hour() == 10 && now.minute() == 1 && now.second() == 0){
digitalWrite(10, HIGH);
delay(505);
digitalWrite(10, LOW);
delay(505);}
if (now.hour( ) == 11 && now.minute( ) == 1 && now.second( ) == 0){
digitalWrite(10, HIGH);
delay(505);
digitalWrite(10, LOW);
delay(505);
}
if (now.hour( ) == 12 && now.minute( ) == 1 && now.second( ) == 0){
digitalWrite(10, HIGH);
delay(505);
digitalWrite(10, LOW);
delay(505);
}
```

```
if (now.hour( ) == 13 && now.minute( ) == 1 && now.second() == 0){ digitalWrite(10, HIGH);
delay(505);
digitalWrite(10, LOW);
delay(505);
}
if (now.hour( ) == 14 && now.minute( ) == 1 && now.second( ) == 0){
digitalWrite(10, HIGH);
delay(505);
digitalWrite(10, LOW);
delay(505);
}
if (now.hour( ) == 15 && now.minute( ) == 1 && now.second( ) == 0){
digitalWrite(10, HIGH);
delay(505);
digitalWrite(10, LOW);
delay(505);
}
if (now.hour() == 16 && now.minute() == 1 && now.second( ) == 0){
digitalWrite(10, HIGH);
delay(505);
digitalWrite(10, LOW);
delay(505);
}
if (now.hour() == 17 && now.minute() ==1 && now.second() ==0){
digitalWrite(9, HIGH);
delay(3535);
digitalWrite(9, LOW);
}
}
void Switch1 ( ) {
unsigned long currentMillis1 = millis();//capture current time with reference to when the program
started
unsigned long previousA1 = 0; //store value for when last action was carried out
long intervalA1 = 10; //give interval of 10ms to avoid debounce
if ((unsigned long)(currentMillis1 - previousA1) >= intervalA1) {
bs1 = digitalRead(A2);
previousA1 += intervalA1;
}
if (bs1 == 1) {
digitalWrite(10, HIGH);
delay(500);
digitalWrite(10, LOW);
}
}
void Switch2 ( ) {
unsigned long currentMillis1 = millis( );
unsigned long previousB1 = 0;
long intervalB1 = 10;
if ((unsigned long)(currentMillis1 - previousB1) >= intervalB1) {
bs2 = digitalRead(A1);
previousB1 += intervalB1;
if (bs2 == 1) {
digitalWrite(9, HIGH);
delay(3535);
digitalWrite(9, LOW);
}
```