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Research Article

Performance of Polymer Composite Constituted Cabinet Dryer Integrated within a Solar Flat Plate Collector

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Generally, solar dryer cabinets are made up of sheet metals that are heavy, costly, tend to rust over time, and possess the high heat rate to the outer atmosphere. In order to overcome these drawbacks, this research urges to develop a natural fiber reinforced polymer-based cabinet dryer, specially designed and fabricated for the purpose of solar drying. Nylon is used as the matrix material and *Prosopis juliflora* in particulate form is used as the natural fiber reinforcement. The dryer cabinet was designed at industrial scale to dry 5 kg of ginger at a single setting. This work also studies the efficiency of the polymer composite cabinet integrated with a flat plate solar collector system that is coated with copper and black chrome attached to corrugated fins in between the absorber plate and storage medium. The FRP chamber was compartmented in its interior with aluminium perforated sheets and experimentation was performed to determine the efficiency of the composite cabinet based on reduction of heat loss from the system. The performance of the coating, storage medium materials, and overall storage efficiency were also studied. The FRP cabinet resulted in a moisture level less than 8.5% within 4–7 days. Exergy studies showed 75% efficiency and energy studies gave 25.5 kJ/kg peak readings of drying efficiency for a period ranging between 11 and 12 hours. This was a 75% increment in energy efficiency. Thermal degradation of the FRP material was found to be stable up to 300°C. The overall weight of the constructed polymer cabinet was 25% lesser than the conventional systems.

1. Introduction

Ginger is a popular spice and cash crop all over the world. India, China, Japan, Nigeria, and Indonesia are among the countries that grow it. India is the world's greatest producer and consumer of ginger, accounting for 32.75 percent of global output [1]. The consumption pattern shows that green ginger is used 50% of the time, dry ginger is used 30% of the time, and seed materials are used just 20% of the time. Dried ginger has a large market and is exported due to its medicinal characteristics, which are used to cure stomach aches, nausea, indigestion, asthma, and other ailments [2]. To avoid waste due to microbial and fungal attacks, the economically valuable spice must be dried effectively to achieve a very low moisture content. Drying has traditionally been crucial for preserving agricultural products and extending the shelf life of food [3]. Drying different food products can be carried out in a variety of ways. The traditional open-air drying method has a number of drawbacks. For limiting product deterioration and reducing drying time, numerous energy-based dryers are available. Due to the increasing cost of energy, traditional dryers and drying procedures are not cost effective [4, 5]. Drying has become an energy-intensive and unaffordable practice for farmers due to diminishing fossil fuel supplies and rising costs [6].

FRPs when compared with metals, avoid heat transfer to a greater extent. Polymer composites are sustainable and can be recycled during the end of their service life [7]. They also tremendously help in weight reduction when compared with the existing metal-based structures for solar dryers. Their ability to avoid rusting unlike metals and their inability of undergoing chemical reaction with the product that is to be dried or the fragments and evaporated vapours that are developed by the drying process makes them a significant material to be considered for the proposed application. The natural fiber reinforced plastics provide the cheapest method for fabricating FRPs [8]. Their strength to weight ratio has fascinated researchers to utilize them in versatile applications. Various natural fibers have also been studied for their heat transfer analysis [9]. *Prosopis juliflora* (PJ) is one of the very successful natural wood fibers that has proven high thermal stability and good mechanical character. Previous studies depict that PJ wood has very low moisture absorbance tendency, high thermal stability, and is also a very cheap source of reinforcement [10, 11]. Among the various sizes of natural fibers long, short, and powdered, the small-sized fibers have proven to show better thermal stability which is a key factor to the application that the composite in this research work is being developed for. Hence this research considers PJ as the reinforcement material in the particulate form. Table 1 portrays the chemical configuration of *Prosopis juliflora* natural wood fibers.

Various polymers in literature surveys have been developed by combining natural fibers for thermal-based applications to resist heat transfer. Nylon is selected in this research due to its complex polymeric structure giving it its rugged construction. It is one of the promising polymers that can withstand high temperatures and provides excellent abrasion and good work life [12]. These properties of nylon and PJ ensure a promising output. This project work is one of the first attempts made to fabricate a FRP-based composite cabinet dryer for the purpose of drying agricultural food products. This research examines the reduction of heat loss in the cabinet dryer chamber, the economic feasibility of the developed FRP cabinet, and experimental analysis to evaluate the performance for drying ginger targeting suitability for medium scale farmers and MSMEs. Mechanical properties of biodegradable film based polymers with natural fiber reinforcements have also proven to have shown outstanding performance along with thermal stability and thermal degradation characteristics [13–15].

Natural fiber reinforced composite materials are processed in many different methods based on the end application they are developed for [16]. Among the various methods of processing of polymers such as hand-layup, injection moulding, compression moulding, and in situ, large-sized slabs are found to be best produced using the compression moulding technique especially when natural fiber reinforcements are taken into consideration [17]. McHenry and Stachurski [18] have previously worked with nylon-reinforced eucalyptus wood fibers to fabricate a composite material specifically designed for a fluidized bed for mixing and moisture control applications. Reinforcement quantities of the wood fibers at 2.5, 5, and 7.5 wt% were considered amongst which the 2.5 wt% wood powder reinforced nylon composite had resulted with the highest mechanical characteristics. Morphological characterization had shown excellent adhesion of the wood fibers to the nylon polymer. Thermal degradation of the wood was initially at 120°C which had a drastic improvement of upto 230°C after it was melt mixed into a composite with nylon. A hot press was used to fabricate the composite slabs which resulted in excellent bonding of the matrix and reinforcement materials. Aydemir et al. [19] worked with Nylon 6 reinforced pine wood fibers and maple wood fibers individually to form composites for the automobile industry relating to hood fabrication applications. A 60# mesh size was used to obtain even sized wood particles which were reinforced into nylon at weight ratios of 5, 10, 20, and 30%. Heat-treated wood fibers and untreated wood particles were analysed during the study. Composite compounding followed by the injection moulding technique was followed for the fabrication of the composite specimens. TGA carried out on the composites showed a minimum thermal stability of 200°C for the untreated fibers and higher values for the heat-treated fiber-reinforced composites. Although rheological studies showed that the viscosity of the 20 wt% reinforced composites were very high, the mechanical properties were found to be best for the 20 wt% wood fiber-reinforced nylon composites for both the cases of pine wood and maple wood fibers.

The cabinet dryer is the most practically used space in a solar dryer system for drying farm products. Higher heat retention and low heat transfer from the outer atmosphere and vice versa should be maintained for greater efficiency of the dryer. These factors leads us to the practical thinking of FRP-based composites as an alternative for conventional metal-based walls of the dryer cabinet due to their extensive property of heat transfer resistance between mediums [6, 7]. In this research work, drying of ginger was undertaken to study and investigate the performance of the integrated composite cabinet with a solar flat plate collector.

2. Methodology

2.1. Experimental Design. The solar collector was fabricated to the following dimensions: 750 mm length, 450 mm width, and 180 mm·height; the dimension of the absorber plate was 700×400 sq·mm and 0.8 mm thick [14]. The schematic representation of the solar flat plate collector with a black chrome coated absorber plate is shown in Figure 1. A diverging portion is given at the collector's entry to allow consistent air transmission over the absorber plate, and a convergent pipe with a size of 125 mm length and 45 mm width was used to connect the collector and the drying chamber composite cabinet. The diagrammatical model of the complete setup connecting the dryer solar plate and the composite cabinet tower is represented in Figure 2.

A primary solar collector (0.75×0.45) m is positioned on top of the dryer, which is protected by a transparent glass cover. Forced convection provides fresh air, which is heated as it passes through the solar collector on its way to the drying chamber. It permits solar rays into the drying

Table 1: Chemical configuration of *Prosopis juliflora* natural wood fibers.

Plant/wood fibres	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Wax (wt%)
Prosopis juliflora	61.65	16.14	17.11	0.61

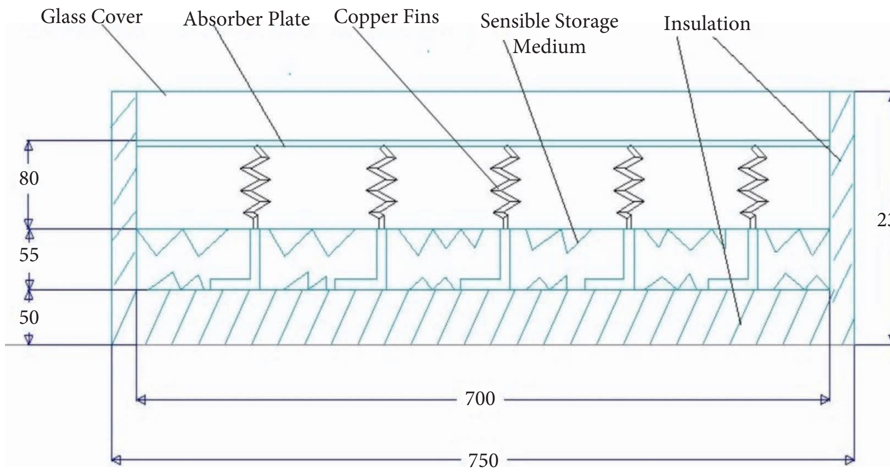

Figure 1: Design of the solar collector plate.

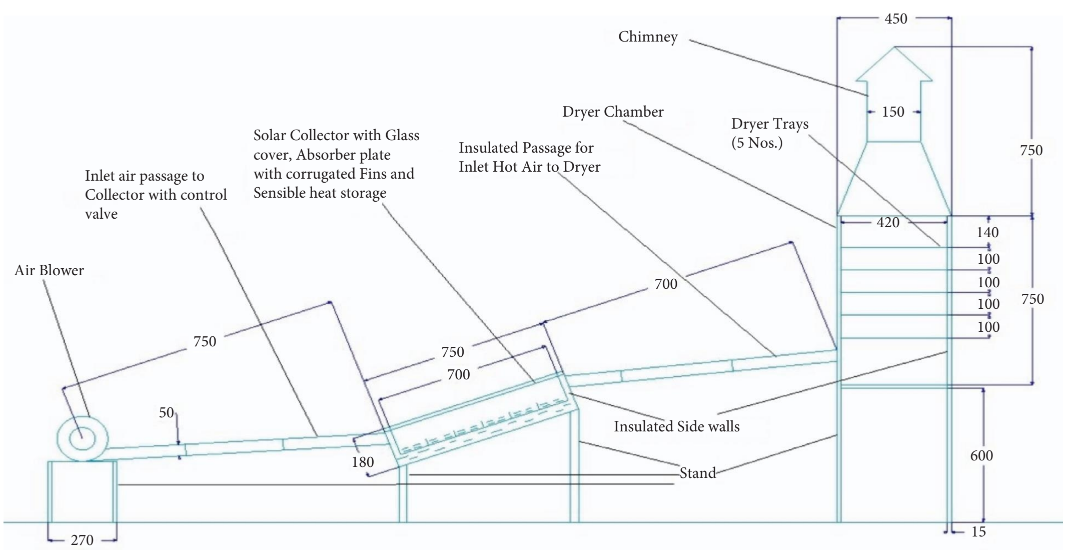

Figure 2: Schematic diagram of the complete experimental setup with the integrated composite dryer unit.

chamber, which speeds up the drying process due to the greenhouse effect. The dimensions of the composite drying chamber are 750 mm height and 450 mm width. Five trays at a distance of 100 mm each were designed and placed at equal intervals inside the composite chamber to facilitate loading of the food products. To allow for improved air circulation, the drying tray comprises of aluminium perforated sheets with a surface area of 380×380 sq·mm. On the sample holding mesh trays, ginger slices (5 kg each batch) with a moisture content of 621.5 percent d.b. were equally distributed. With an electronic balance scale, the weight of the material was carefully measured at predetermined time intervals to analyse the drop in mass due to dehydration. A PT-100 sensor thermocouple with an accuracy of 0.5°C was used to measure the temperature of the air at the inlet and outlet of the solar collector at regular time intervals. The composite dryer cabinet made of fiber-reinforced plastic (FRP) had a wall thickness of 10 mm. All direct experimental data that were noted manually and using sensors were tabulated and then provided as input to the Origin 8 version software to obtain precision graphical representations of the results.

2.2. Fabrication of the FRP Cabinet Material. Nylon 66 was obtained from the Central Institute of Plactic Engineering Technology at Hyderabad in India. The nylon was in tiny granular form in its virgin state. It had a specific gravity of

1.14 grams/cc and a melting point of 223°C as denoted by the supplier. PJ wood was initially obtained from Namakkal district in Tamil Nadu, India, and the wood was dried in a furnace at 80°C for 48 hours to get rid of moisture in the fibrils. Then, the wood was sized down using machinery as performed in previous experimental works by the authors [10, 15] and finally sieved using a 400# mesh size to obtain the equally sized fine powder. The powdered PJ was initially dry mixed with nylon granules in calculated weight fraction ratios of 80 : 20. The literature records that 20 wt% reinforcement of natural fiber particles into polymers deliver composites with the best mechanical character [8, 11]. Then, the dry mixed materials were blended using a twin screw extruder at 240°C and a rotary screw speed of 100 rpm. This process ensured that the nylon and the PJ fiber were blended with each other completely and were obtained in the form of composite pellets. These composite pellets were then placed in the compression moulding machine and fabricated into large slabs of dimensions 750 × 450 mm and uniform thickness of 10 mm. The compression moulding process was performed at a pressure of 6 bar and a temperature of 240°C for a period of 12 hours. The final product was then constructed into the outer layer walls of the drying cabinet using mechanical fixtures. Test specimens of the fabricated composite material were cut from the large slabs and were tested for thermal stability using thermogravimetric analysis (TGA) [15] and the water absorption rate to ASTM D570 [20].

2.3. Experimental Calculations

2.3.1. Determination of the Moisture Content of Ginger. The formulae used to calculate the wetness of ginger using the solar dryer system are tabulated in Table 2 and represented through equations (1–6). Physical errors such as fixed errors, manufacture errors, and random errors were considered while other parametric errors such as relative humidity, moisture loss, weight loss, solar intensity, and air velocity errors were also considered during the experimental phase.

2.3.2. Economic Analysis. Any system's economic viability is determined by doing an economic study of the system. It is critical to determine whether a new technology is economically viable before it can be successful and commercialized. In this study, a variety of economic variables were utilised to assess the economics of a hybrid sun-drying system. The total capital cost (C0) of the designed system is calculated using equation (7) [27]. The parameters and their respective formulae that were considered for the economic analysis of the drying system are tabulated in Table 3 and are represented thorough equations (8)–(10).

$$\text{CO} = \text{cost of materials used for fabrication of system} + \text{labour cost} \quad (7)$$

In Table 3, C0 is the fabricated dryer's capital cost in rupees, t is the dryer's life span (year), P is the daily benefits gained from the dryer in rupees, n is the number of days of operation per year (day), R is the repair and maintenance cost in rupees, and D is the discount rate (%).

3. Results and Discussion

The curve of dryer efficiency during drying is shown in Figure 3. The range of dryer efficiency during drying ginger was in the range of 4.16–46.72%, respectively. The average dryer efficiency of dried ginger was 28.96%, respectively. It can be seen that using higher drying temperature would increase the dryer efficiency. This happens because higher drying temperature used will generate more heat, which will increase the moisture uptake by drying air and speeds up the drying process. This will increase the dryer efficiency [28]. This research showed results that coincide with few previous studies. A solar LPG hybrid dryer applied for drying shrimps where the dryer efficiency was varied from 24.21 to 37.09%, with the average value of 29.93% [29]. A second study used cassava as the product to be dried. The dryer efficiency was found to be 30% with an increase from 16%. Drying temperature was increased from 40°C to 60°C [28, 29]. Another study reported an average dryer efficiency value of 27.1% during seaweed drying using a solar tray dryer [30].

3.1. Quality of Dried Ginger. Four quality parameters of dried ginger were tested in this experiment based on the following criterion: aroma test, fat content, ash content, and presence of moulds and insects during storage. During the quality test, there were no changes in aroma of the dried ginger. Also, no mould formation or insects was seen to develop and the nil traces of fungal formation were endured during storage of dried ginger. Both the fat and ash content of dried ginger have satisfied the range of their respective standard value. The fat content decreases with higher temperature (4.46% to 2.73%, for 40 to 60 degree, respectively). This happens because higher temperature will tend to deactivate the enzymes, thus halting the production of volatile fatty compounds and reducing the fat content [31]. However, drying helps to conserve the bioactive compounds and unsaturated fatty acids which are more adequate for consumption [32]. The drying behaviour of ginger was achieved maximum between 12 pm and 2 pm where the hot air was set at 60°C. The highest temperature recorded was 61°C. The moisture content of ginger decreased drastically with increased drying time and reached a constant value after due course of time.

3.2. Energy and Exergy Analysis. As incurred from the first law of thermodynamics, energy gain and energy utilised were estimated for the solar collector system, while exergy data were interpreted relating the second law of thermodynamics to govern the type of exergy losses, magnitude and the location during the drying process. Exergy loss was seen to be dominant at the final trays due to the low utilization of the available energy. Despite the energy utilization ratio and exergy efficiency of drying ginger varied from 15.3 to 25.4 kJ/kg and 57.5 to 78.95%, and the ginger was sufficiently dried between the temperature ranges of 40°C–60°C and

Table 2: Formulae used to calculate the wetness of ginger using the solar dryer system.

Equation number	Description/parameters	Formulas	References
(1)	The initial moisture content (M), m_i represents the mass of wet ginger in (g) and m_d represents the mass of dry ginger (g)	$M = (m_i - m_d/m_i) \times 100$	[21–24]
(2)	The amount of water content (W) removed	$W = M_i - M_f/100 - M_f \times W_o$	[21–24]
(3)	Instantaneous moisture content Mt is calculated for time 't'	$M_t = [((M_t + 1)W_t/W_o) - 1]$	[21–24]
(4)	The moisture ratio MR	$\mathrm{MR} = ((M_t - M_e)/(M_i - M_e))$	[21–24]
(5)	Since equilibrium moisture (Me) is very less compared to initial moisture	$\mathrm{MR} = (M_t/M_i)$	[25]
(6)	Drying system efficiency is a measure of a drying system's overall efficacy, indicating how well the input energy is used to dry the product; the energy usage for the blower can be used to calculate the forced convection dryer efficiency	$\eta_d = (\mathrm{WL}/A_s I + P_f)$	[26]

Table 3: Formulae used for the economic analysis of the drying system.

Equation number	Description/parameters	Formulas	References
(8)	Net worth (NW) of the drying system	$\eta_d = (\text{np} - \text{co}\alpha/d)\ ((1 + d)^t - 1/1 + d)$	
(9)	Benefit-cost ratio	BCR = (total benefit received per year/capital cos t de veloped system)	[26, 27]
(10)	Payback period (PP)	$\text{PP} = (\text{co}/(\text{np} - \alpha\text{co}))$	

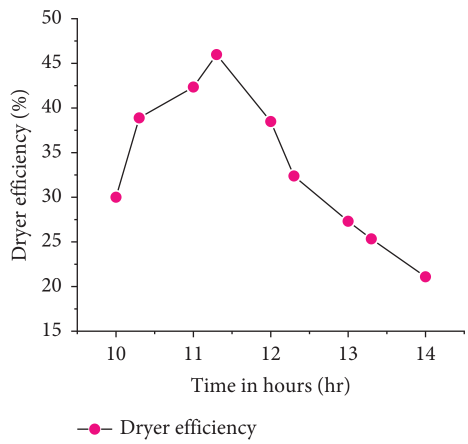

Figure 3: Dryer efficiency curve for drying ginger.

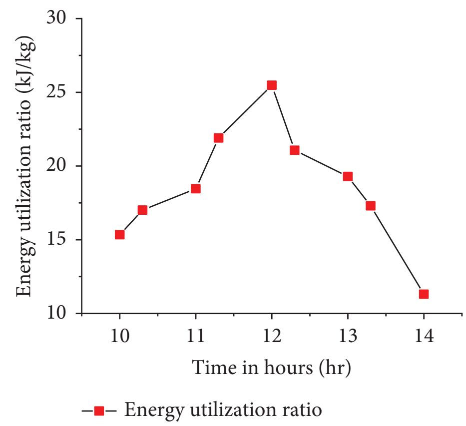

Figure 4: Variation of the energy utilization ratio with the dehydrating period.

36°C–63°C at a relative humidity of 1.243 m/s and an air flow time of 6 hours [33]. The reduced sun radiation during the evening hours was not taken into consideration since the literature states that the efficiency of the dryer cabinet since preheating using coarse aggregates help in reducing the heat loss. Hence, the exergy performance quantifies the energy loss in the solar-based system that is still based on the second law of thermodynamics. The energy and exergy performances are graphically depicted in Figures 4 and 5, respectively.

3.3. Economic Analysis of the Developed System. The created dryer's economic analysis and related factors are based on India's economic circumstances. For ginger drying, a cost-benefit analysis was conducted using the annualised cost technique. 5 kilograms of ginger took 6 hours to dry in a solar dryer. On a clear sunny day, 5 hours of drying time is available on average. For a year, 200 days were counted as clear sunny days. The solar dryer's capital cost is estimated to be Rs. 30,000. The solar dryer's annual repair and maintenance costs are calculated at 5% of the annual capital cost. Drying cost for 5 kg of ginger with a solar dryer was estimated to be Rs. 61 per day. In season, raw ginger costs Rs. 20 per kilogram. The amount of electricity required to dry 5 kg of ginger is 1.5 units. Dried ginger is worth Rs. 160 on the market, and the daily benefit from drying is Rs.77. The annual cost of a specially developed drying system for ginger is Rs. 21,700. The benefit-to-cost ratio of the solar dryer that was designed was found to be 2.41. The cost-benefit ratio was computed. The developed FRP cabinet dryer had a payback period of only 6 months. When compared with the conventional solar-drying hybrid system, the payback period is short. As a result, FRP solar drying systems are cost effective. The usage of a solar dryer cut the drying time in half. It can be seen from Figure 6 that the ambient temperature varied from 26 to 28.96°C while the solar intensity varied between 721.54 and 1027.72 W/m^2, with the average of 780.13 W/m^2.

Ginger drying was tested for thermal performance and drying qualities. The moisture content of ginger decreased from 83.3% to 10.41%, respectively, all on wet basis as shown Figure 7. The similar equilibrium moisture content results

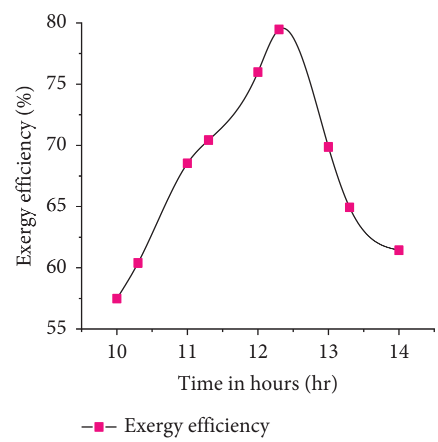

Figure 5: Variation of exergy efficiency with the dehydrating period.

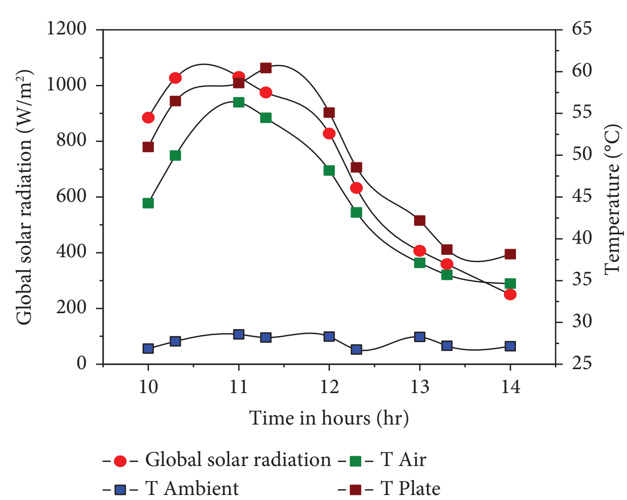

Figure 6: The profiles of temperature and solar intensity during solar drying of ginger.

were reported by several research work on potatoes [34], tomatoes [35], bananas [36], and cucumbers [37]. The net benefit, benefit-to-cost ratio, and payback duration were

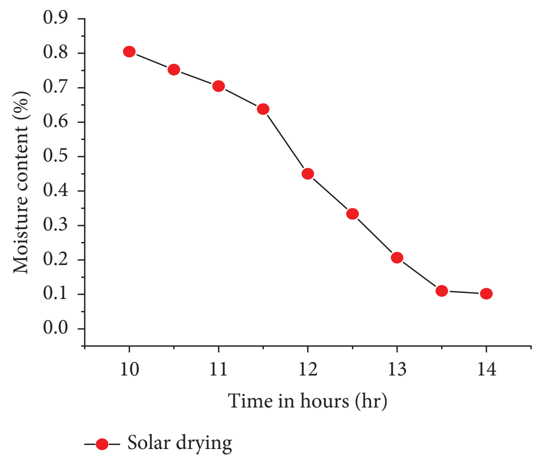

FIGURE 7: Drying characteristics of ginger with respect to drying time.

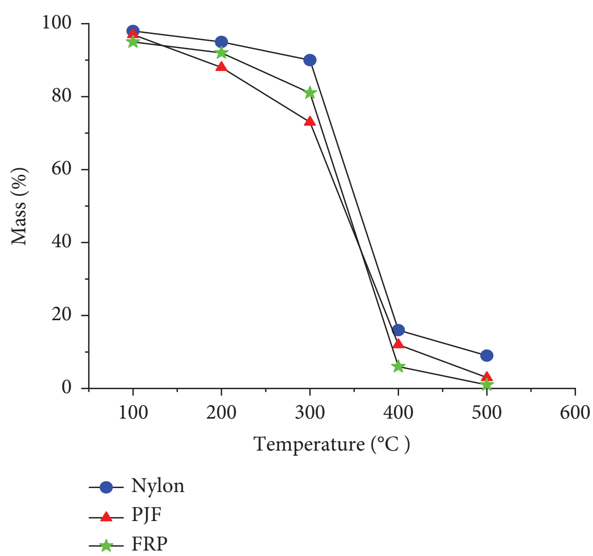

FIGURE 8: TGA curves of the cabinet dryer materials.

calculated using economic analysis and it proved the devices' economic viability.

3.4. Thermal Properties of the FRP. A minor amount consisting of a 50 milligram sample was taken from the developed composite material to carry out the thermal studies. The specimen was placed in the crucible of a thermogravimetric analyzer apparatus of Model: S11TG/DTA 6300 for analysing the thermal stability, thermal degradation initiation and progression, and the complete degradation with postresidue. All the properties of the specimens were analysed while maintaining the inner equipment environment with nitrogen gas. The variation of temperature was set at an increment rate of 5°C per minute. The testing was performed between the temperature range initiating from 20°C upto a maximum limit of 500°C [38]. Thermal stability of the composite was checked in comparison with plain nylon polymers as well as plain PJF wood powder. The thermal degradation of nylon was highest and addition of PJ wood powder as reinforcement acting like a thermal barrier similar to a ceramic wool reinforcement in an exhaust system [39]. Significant amount of thermal stability increment was noticed which was calculated to be sufficient enough for the described application. The maximum temperature of thermal stability of the composite material was 200°C beyond which marginal degradation showed reduction in a mass of the composite upto 80%. Further increment in the temperature showed abrupt degradation turning the mass of the composite from 80% to 10% at 400°C. Beyond this point minimal residue of the composite was found. The TGA curves are depicted in Figure 8.

Thermal properties of the FRP as tabulated in Table 4 were analysed. Thermal properties were found to be suitable at the maximum internal temperature held within the solar cabinet during the experimental phase when compared to other conventionally used materials. Hence while using the FRP walled cabinet dryer, it is not necessary to provide an additional layer of glass wool, which is a common practice followed while using sheet metal based dryer cabinets. Water

Table 4: Thermal properties of the PJ-reinforced nylon FRP composite.

Thermal conductivity	Melting point	Maximum service temperature	Vicat softening point	Thermal degradation
0.200–0.330 W/m-K	200–240°C	80–210°C	150–260°C	320°C

absorption carried out to ASTM D570 for a period of 24 hours showed a negligible absorption rate of 0.06%. This was due to the natural tendency of the fiber to absorb moisture.

4. Conclusion

(i) The thermal efficiency of the FRP cabinet dryer was found to be 12% more efficient than the conventional metal sheet based cabinet models and had an overall weight reduction of the equipment by 25%. The polymer cabinet dryer is one of the most hygienic and eco-friendly process.

(ii) Metal-based dryers can harm the food source due to toxicity that appears by reaction of chemicals between the metal and the ginger juice; it makes the food material less appetizing. This is prevented when the polymer cabinet is used as an alternative. It is also an economical and sustainable method of drying.

(iii) It can be concluded that the solar drying method introduced in this study is suitable for ginger as well as other food materials and much faster compared to other conventional methods, while still able to maintain the quality of product. The developed FRP cabinet dryer is more suitable to dry the agricultural products and it is environment friendly in terms of avoiding harmful gaseous reactions that may be emitted by the food products or the conventional sheet metal glass wool method. It is also found to be more economical and lighter in weight when compared with conventional solar dryer cabinets.

(iv) It was found that final moisture content of ginger dried between 40 and 60°C gives the best result. However, the maximum drying was achieved between 11 and 12 hours, which is much faster than other ginger-drying studies using other types of dryers. It is assumed that ginger drying takes place primarily during the falling rate period, as evidenced by the decreasing value of the drying rate over time.

(v) It was seen that the solar drying system made up of nylon and PJ combined composite reduces heat loss and does not affect the aroma of ginger. The exergy efficiency of the dryer varied from 19.1% to 78.8%. The overall energy efficiency of the dryer was 73.6% through which observations showed that 1000 grams of ginger had been efficiently reduced by mass weight to 369.77 grams after the drying period. This is considerably as effective as the heavy and costly metal-based dryers.

(vi) Energy values showed a peak at 26°C at a 12 hour time duration and exergy peaked at 80% for the respective time duration. Economic analysis revealed a benefit-to-cost ratio of 2.41. This proved increased energy savings for a calculated period of 6 months.

(vii) Thermal stability of the nylon-PJ composite material was stable upto 310°C beyond which degradation stated and the complete degradation took place at 400°C leaving behind a 5% residue at 500°C. This proves that the material is optimally suitable for the application that it was developed for.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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