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ORIGINAL ARTICLE

Design and development of biomass-fueled convective dryer for marine products: energy, exergy, environmental, and economic (4E) analysis

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Abstract
The study aimed to design a biomass-fueled convective dryer and evaluate its performance using anchovy and shrimps. The dryer comprised a biomass furnace, a blower, a drying chamber, stainless steel trays and a chimney. The heat energy for drying was supplied indirectly through ducts by combustion of woody biomass in the furnace. Anchovy had an initial moisture content of 525% dry basis (d.b) and reduced to 17.18% (d.b) within 3.5 h, while the shrimp reached a final moisture content of 18% (d.b) in the same time frame. The logarithmic model was selected as the best fit for anchovy and shrimp drying, with R^2 values of 0.9989 and 0.9998, RMSE values of 0.0016 and 0.0021 and chi-square values of 0.00033 and 0.00047, respectively. The effective moisture diffusivity of anchovy and shrimp was found to be 6.01×10^{-7} m^2/s and 1.78×10^{-6} m^2/s, respectively. The thermal efficiency of anchovy and shrimp was calculated as 21.23% and 24.15%, respectively. The shrinkage (%) and rehydration ratio of shrimp and anchovy were within the acceptable limit. The energy payback period of biomass dyer was estimated to be 0.27 years. The sustainability index and environment destruction coefficient of the biomass dryer were 1.62 and 2.62, respectively. The waste energy ratio, environmental impact factor and improvement potential of the dryer were determined as 0.618, 1.69 and 0.4408, respectively. The study obtained favourable techno-economical feasibility results for biomass drying of shrimp and anchovy indicating that it can be recommended for large-scale drying of marine foods.

Keywords Shrimp · Anchovy · Modelling · Sustainability Index · Payback period · Shrinkage

1 Introduction

Drying aims to limit the moisture content in foods to a certain level for nutritional, functional and commercial stability [1]. It preserves perishable agricultural and marine products, contributing to lesser post-harvest losses [2]. Traditionally, the drying of foods is achieved under solar radiation, which is highly economical and widely adopted [3]. However, the requirement for achieving hygienic and quality dried products has necessitated the need for a controlled and faster drying process [4]. Mechanical dryers using renewable-based energy sources were found to be hygienic, economical and environmentally compatible as compared to electrical dryers [5]. Alfiya et al. [6] reported that 32% of the energy consumption of developing countries is met from biomass sources, of which 90% is applied in the food sector. Wood, having a calorific value of 17,000–19,000 kJ/kg can be used as the source of energy for the biomass dryer. It is reported by Lauri et al. [7] that woody biomass is capable of satisfying primary energy needs up to 18% by 2025.

Biomass-based drying systems find application in a wide range of crops [3]. Rizal and Mohammed [8] fabricated a solar-biomass dryer for the controlled and hygienic production of dried fish. The dryer reduced the moisture content of fish to 12% within 15 h of operation with 45 kg of wood fuel input. They also reported the net present value and payback period of $21.09 and 2.6 years, respectively. Similarly, Yuwana and Sidebang [9] constructed a solar-biomass hybrid dryer and tested its performance under solar, biomass and combined modes. Moisture contents of fish were reduced to 20% within 24.4 h, 14.4 h and

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15.4 h under solar, biomass and combined modes, respectively. The study recommended biomass drying for large-scale adoption for farmers and fish processors. Chavan et al. [10] studied the drying characteristics of mackerel under solar-biomass and sun drying. The moisture content of mackerel was reduced from 75 to 16% under both drying conditions. The study confirmed that mackerel dried under solar-biomass drying exhibited superior properties in terms of biochemical, microbiological and organoleptic aspects. Murali et al. [11] evaluated the drying of shrimp under a biomass gasifier integrated solar hybrid dryer using coconut shells as biomass fuel. The moisture content of shrimp was reduced to 18%, 16% and 17%, within 6 h, 9 h and 6 h of operation under hybrid, solar and gasifier modes, respectively.

The conventional electrical hot-air dryers were not affordable to farmers, fishers and other stakeholders due to their higher operational cost [12]. The development of biomass-based drying systems is found to address the issue of power consumption to a larger extent [13]. However, the lack of a properly designed biomass drying system for bulk drying of marine products has led to reliance on traditional sun drying methods for drying shrimp and other fishery products [14]. Murali et al. [11] reported that sun-dried products fetch a lower margin in the market as compared to industrially dried products due to their unhygienic method of production. The authors also opined that biomass dryers with controlled drying conditions are found to stabilise the income of the vulnerable population with fishers in coastal areas. Prasad and Vijay [15] elaborated on the practical advantages of biomass drying and mentioned that inputs for running the system can be directly obtained from the farmer fields and other means.

A study reported that carbon emissions into the environment increased in the range of 18–22 Gt between 2011 and 2019 [16]. Stahl et al. [17] reported that 19% of the greenhouse gas emissions arise from the food processing-related sector. In this context, it is essential to study biomass-based drying systems for their energy, exergy, environment and economic implications for the industry. However, a very limited study was carried out by the researchers on 4E (energy, exergy, environmental and economic) analysis of biomass drying unit. In addition, literature on quality aspects of biomass-dried marine products is meagre on industrial applications.

To the best of our knowledge, no data is available on the performance evaluation of shrimp and anchovy in biomass-convective dryers using wood as fuel. Hence, an attempt was made in this study to develop a biomass-fired convective dryer, evaluate the drying kinetics and carry out 4E (energy, exergy, environmental and economic) analysis for drying shrimp and anchovy.

2 Material and methods

2.1 Samples

Fresh anchovy and shrimp were procured from Chellanam fishing harbour, Kochi. The length, breadth and thickness of the anchovy were 44.0 ± 3.0 mm, 7.5 ± 1.5 mm and 3.0 ± 2.0 mm, respectively. The length, width and thickness of shrimps were 41.25 ± 0.75, 2.25 ± 0.15 and 0.8 ± 1 mm, respectively. The samples were washed in clean water and left to drain. The drained samples were loaded into the dryer for conducting the drying studies.

2.2 Design and fabrication of biomass convective dryer

A batch-type biomass dryer operating under a forced air circulation system was designed and fabricated for drying marine products. The assumptions considered for dryer design are given in Table 1.

2.2.1 Energy balance for drying

Energy balance in drying was determined using the equation suggested by Youcefali et al. [18].

$$M_w L = m_a C_p (T_i - T_f) \tag{1}$$

2.2.2 Moisture removal during drying

The quantity of water removal from the samples was calculated as described by Delfiya et al. [4],

Table 1 Dryer design assumptions and considerations

S. No	Items	Details
1	Loading capacity	50 kg fresh product
3	Moisture content (initial)	75–80% (w. b)
4	Moisture content (final)	15–20% (w. b)
5	Dryer temperature	50–60 °C
6	Air velocity	1–1.5 m/s
7	Ambient temperature	25–35 °C
8	Ambient relative humidity	70–90%
9	Latent heat of vaporization of water	2260 kJ/kg
10	Specific heat capacity of air	1 kJ/kg °C
11	Density of air	1.225 kg/m^3
13	Specific heat of water	4.186 kJ/kg °C
14	Drying period	5–6 h

$$M_w = \frac{W_i(M_i - M_f)}{100 - M_f} \quad (2)$$

2.2.3 Mass of air required

The requirement of drying air was estimated as reported by Alfiya et al. [6],

$$M_a = \frac{M_w L}{C_p(T_i - T_f)} \quad (3)$$

2.3 Description of developed biomass-fueled convective dryer

The drying unit contained a biomass furnace (30 kg), a blower, a drying chamber, perforated trays and exhaust. The combustion of biomass in the furnace generated heat required for the drying of samples. The combustion transfers the heat to the ambient air which in turn gets heated up. The resulting hot air is then circulated to the drying chamber with the help of a blower. The dryer consisted of perforated trays stacked one over the other with a total spread area of 14.40 m^2. A schematic drawing of the developed dryer is presented in Fig. 1. The novelty in the design of the dryer lies in the mode of arrangement of trays. Trays are arranged vertically and parallel to the combustion chamber, to achieve cross-flow heat transfer for better thermal efficiency. The technical specifications of the biomass-fueled convective dryer are presented in Table 2.

2.4 Drying procedure

The fish drying experiments in the biomass drying unit were carried out from January to February 2023 at CIFT, Kochi.

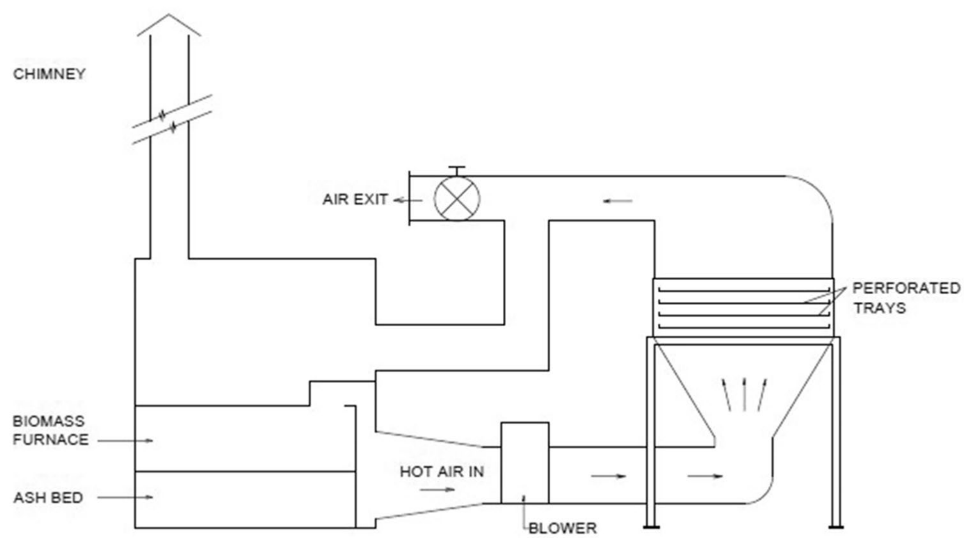

Fig. 1 Schematic diagram of developed biomass-fueled convective dryer

Table 2 Technical specifications of biomass-fueled convective dryer

S. No	Loading capacity	50 kg
1	Material of construction	PUF panels with SS 304 inside and powder-coated GI outside
3	Dimensions	1.2 m × 1.0 m × 2.4 m
4	Heat source	Biomass
5	No. of trays	10
6	Tray dimensions	1.6 m × 0.9 m
7	Total tray area	14.4 m^2
8	Tray material	18 Gauge, SS 304, perforated mesh tray
9	Tray material	SS 304
10	Blowers	1 No, 1.5 hp
11	Thickness of insulation	60 mm
12	Suitable products	Fish and fishery products

The experiments were conducted in triplicates with each trial consisting of a 20 kg of fish sample. Drying chamber air temperatures were measured using a J-type thermocouple. The relative humidity of drying air varied from 72.4 ± 1.5 to 37.0 ± 1.5% throughout the drying period. The relative humidity of the ambient air was in the range of 72.4 to 76.5%, which was reduced due to the heat load from the flue gases. Initially, the rate of heat transfer was high due to the vapour pressure gradient between the drying medium and the product samples. This resulted in exhaust air with high relative humidity (72.4 ± 1.5%) at the beginning of drying. As the drying progressed, the moisture content of the samples decreased and hence the vapour pressure gradient also decreased. This resulted in exhaust air with low relative humidity (37.0 ± 1.5%). The velocity of air was measured with an anemometer (Make: Kusam, Meco, KM-732, India). Around 23 kg of firewood was utilized for each experimental run of shrimp and anchovy. Wood material was fed into the combustion chamber in the form of planks 60–75 cm in length, 5–7.5 cm in width and 3–4 cm in thickness. Firing of planks was done and the gate of the furnace was closed tightly before the start of the combustion process. Combustion in the presence of air occurred and the flue gases were transmitted through the duct to the chimney. In this process, the heat energy was supplied to the ambient air that acted as the drying medium.

2.4.1 Determination of calorific value of firewood

The calorific value of firewood was determined using a bomb calorimeter (model XRY-1C Shanghai Changji Geological Instrument Co. Ltd., China). The principle of complete combustion in excess oxygen and 30 atm pressure was employed to generate the heat value of the raw material. The heat released during the explosion process was used to arrive at the calorific value of firewood using the ASTM standard method.

2.4.2 Moisture content

The following equation was used to determine the moisture in the product,

$$M_w = \frac{W_I - W_F}{W_I} \times 100 \quad (4)$$

$$M_d = \frac{W_I - W_F}{W_F} \times 100 \quad (5)$$

2.4.3 Drying rate

The drying rate is the quantity of water removed in unit time and was calculated as given below,

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (6)$$

2.4.4 Moisture ratio

The moisture ratio was estimated as given below,

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (7)$$

The term M_e is removed from the MR equation as it is a very low value and negligible compared to other terms as reported by Murali et al. [5].

$$MR = \frac{M_t}{M_0} \quad (8)$$

2.4.5 Effective moisture diffusivity

The rate of moisture migration in samples during drying is expressed as diffusion and is determined as the moisture loss from the sample. Diffusion is quantified as the effective moisture diffusivity which is determined from Fick's law of diffusion. Fick's law presents moisture migration inside the material in the falling rate drying as:

$$\frac{\delta M}{\delta t} = \nabla.\left(D_{eff} \nabla M\right) \quad (9)$$

Diffusivity calculations were carried out assuming that the samples are cylindrical in shape. For an infinite cylinder, the assumptions and the final equation are obtained from Murali et al. [5],

$$D_{eff} = -\frac{Br^2}{b_1^2} \quad (10)$$

where b is equal to 2.41.

2.4.6 Thermal efficiency

The thermal efficiency of the drying unit is taken as the ratio of heat utilized to the heat energy supplied to the system. The total heat supplied was calculated as the heat energy supplied by fuel and transmitted by the blower. The heat energy supplied by the fuel was calculated as the product of the calorific value of firewood, mass of firewood and duration of drying, whereas the energy consumed by the blower was determined as the product of the rated power of the blower and the duration of drying. Heat energy utilized by the dryer was obtained as the product of the mass of water evaporated and the latent heat of vaporization of water.

$$\eta_{\text{thermal}} = \frac{\text{Mass of water evaporated (kg)} \times \text{Latenet heat of vapourization of water (kJ/kg)}}{\text{Mass of wood (kg)} \times \text{Clorific value of wood} \left(\frac{\text{kJ}}{\text{kg}}\right) + [\text{Power consumed by the blower} \left(\frac{\text{kJ}}{\text{s}}\right) \times \text{drying time (s)}]} \quad (11)$$

2.5 Modelling of drying behaviour

To model the drying behaviour of samples, the drying data were entered in the thin layer drying equations. Non-linear regression analysis was performed, and solutions to the model constants were obtained using MATLAB (R2022a) software. The most suitable drying model was selected based on the maximum value of the coefficient of determination (R^2), lower root mean square error (RMSE) and reduced chi-square (χ^2) value.

2.6 Rehydration ratio

The rehydration ratio measures the cellular and structural degradation of the sample due to the drying conditions. The rehydration ratio was obtained by standard protocols adopted by Doymaz and Ismail [19].

$$\text{Rehydration ratio} = \frac{\text{Weight of rehydrated sample (g)}}{\text{Weight of dried sample (g)}} \quad (12)$$

2.7 Shrinkage

Shrinkage happens due to changes in the volume of food material during drying. The volumetric changes are measured by considering the dimensions of the samples before and after drying using a vernier calliper. The percentage of shrinkage was determined as follows,

$$\text{Shrinkage}(\%) = \frac{D_{\text{Initial}} - D_{\text{Final}}}{D_{\text{Initial}}} \times 100 \quad (13)$$

2.8 Exergy analysis

The component of energy that can be utilized for useful electrical/mechanical work is termed 'exergy' or usable energy. The fraction of energy not fit for useful work is taken as wasted exergy. The efficiency of thermal energy-based systems is better interpreted using exergy analysis. Entropy or randomness resulting in irreversibilities makes the exergy at the output of the system to be lower than the exergy at the input [16]. However, the estimation of exergy is essential in assessing the potential of extracting useful work from a system. Overall exergy is calculated as,

$$E_x = mC_p[\left(T - T_a\right) - T_a\ln(\frac{T}{T_a})] \quad (14)$$

$$Ex_{\text{loss}} = E_{xi} - E_{xo} \quad (15)$$

$$\eta_{Ex} = \frac{E_{xo}}{E_{xi}} = 1 - \frac{Ex_{\text{loss}}}{Ex_i} \quad (16)$$

2.9 Environmental impact analysis (EIA)

The sustainability of drying systems is assessed by the economic viability and environmental stability. The environmental stability of a biomass dryer is determined by its carbon dioxide emission, which depends on embodied energy. Embodied energy represents energy input from sources like firewood/fuel, electricity and the energy embedded in the raw material. EIA is calculated based on formulas presented in Table 3.

Table 3 Environmental impact study of biomass dryer

No	Sustainability criteria	Formula
1.	Energy payback period (EPBP)	$\frac{\text{Embodied energy}}{\text{Annual energy output}}$
2.	Carbon emissions (CE)	$\frac{\text{Embodied energy} \times 0.98}{\text{Life time}}$
3.	Earned carbon credit (ECC)	Net mitigation of carbon dioxide in lifetime X cost of carbon credit
4.	Sustainability index (SI)	$\frac{1}{1-\eta_{Ex}}$
5.	Environmental destruction coefficient (EDC)	$\frac{1}{\eta_{Ex}}$
6.	Waste exergy ratio (WER)	$\frac{E_{xloss}}{E_{xin}}$
7.	Environmental impact factor (EIF)	$\text{WER} \times \frac{1}{\eta_{Ex}}$
8.	Improvement potential (IP)	$1 - \eta_{Ex} \times E_{xloss}$

2.10 Economic analysis

The economic viability and commercial sustainability of the developed biomass dryer unit for drying shrimp and anchovy were assessed in this study. Economic parameters like Annual savings, payback period and benefit–cost ratio were determined as per the procedure reported by Philp et al. [20] and Dutta et al. [21].

2.11 Uncertainty analysis

Uncertainty analysis is crucial for determining the accuracy of measurements involved in drying studies. The uncertainties involved in the parameters such as weight loss, temperature, air velocity, relative humidity, moisture content, drying rate and drying efficiency are estimated by Ferrari et al. [22]. The values of uncertainties of various parameters are tabulated in Table 4. Factors during experiments like selection, calibration, reading, observation, procedures and environment can contribute to uncertainties [1]. Denoting W as the total uncertainty of the nth factor, uncertainty can be expressed by the equation:

Table 4 Uncertainties associated with drying parameters

S. No	Parameter	Value
1.	Temperature	±0.40 °C
2.	Weight loss	±0.55 g
3.	Air velocity	±0.14 ms^{-1}
4.	Relative humidity	±1.5%
5.	Moisture content	±0.29%
6.	Drying rate	±0.10 g/g dm.h
7.	Drying efficiency	±2.46 %

$$W = [(X_1)^2 + (X_2)^2 + (X_3)^2 + \cdots_{..} (X_n)^2]^{1/2} \tag{17}$$

The present study culminated with an uncertainty factor of 5.44%.

3 Result and discussion

3.1 Drying of shrimp and anchovy in biomass dryer

The moisture content of anchovy reduced from 84 to 14.66% (w.b.) (525 to 17.18%, d.b) during biomass drying in 3.5 h (Fig. 2). Moisture content of shrimp reduced from 79.46 to 15.25% (w.b) (387 to 18%, d.b) with a drying rate of 2.72 in 3.5 h. The drying rate (g/g drymass.h) showed an initial maximum value of 3.16 which finally declined to 1.45, towards the end of drying (Fig. 3). Moisture ratio during biomass drying ranged from 1.0 to 0.0327. Dongbang and Pirompugd [23] reported a study on the drying of anchovies in a fluidized bed dryer. They noticed that moisture content was brought down from 412 to 16% (d.b) in 64–172 min under drying temperatures of 70–120 °C. Initially, the moisture content in the anchovies is at a higher level that upsurges the temperature gradient between the samples and the heating medium during drying. This caused comparatively enhanced drying rates at the beginning of drying. As the drying proceeds, the temperature gradient decreases which in turn reduces the rate of drying. During drying, the free and bound water from the anchovies was removed till it reached a moisture content of 17.18% [24]. The pattern of moisture ratio exhibited in the biomass drying of anchovy is in line with the results of open sun drying of prawn and chelwa fish by Jain and Pathare [25].

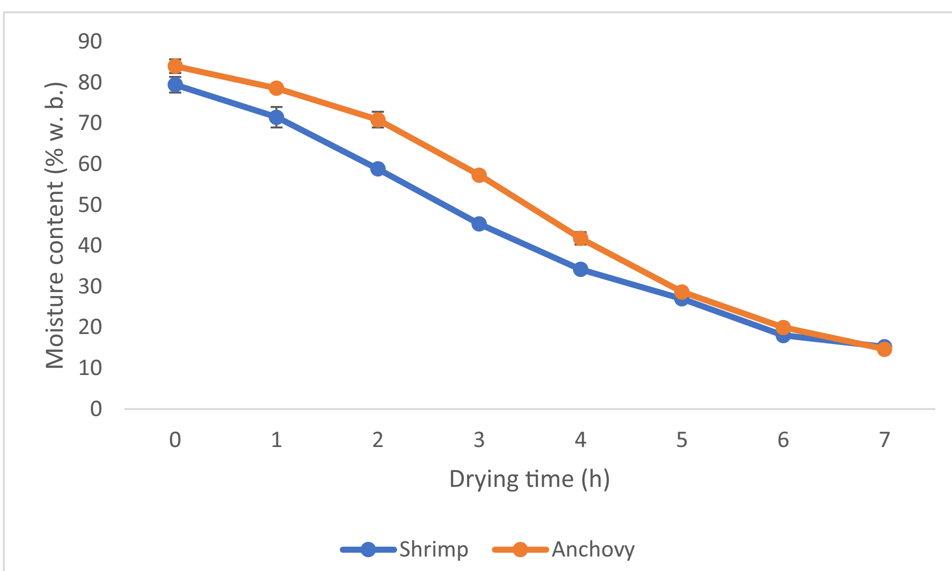

Fig. 2 Moisture content against drying time for biomass drying of anchovy and shrimp

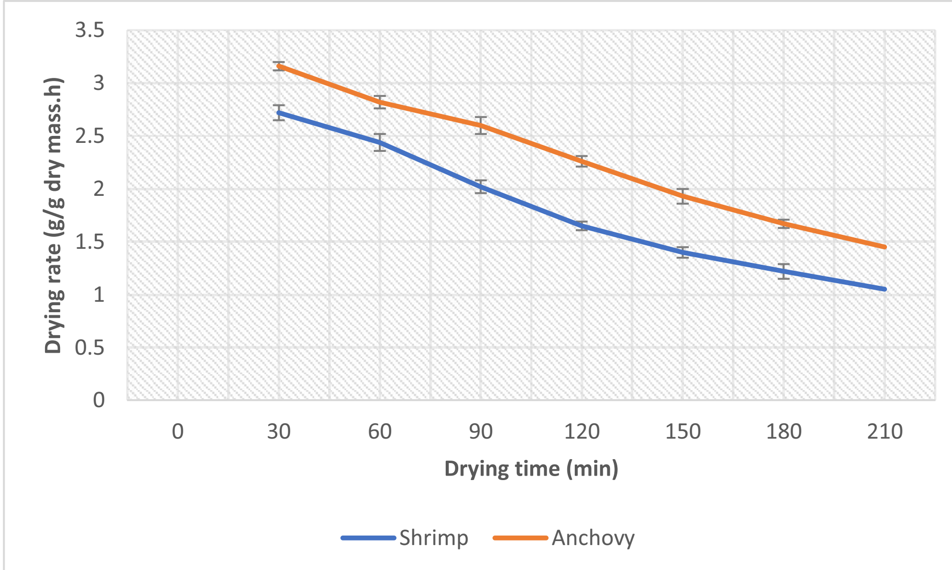

Fig. 3 Drying rate against time for anchovy and shrimps

3.2 Evaluation of drying model

The drying models predicted the best-fit conditions for biomass drying of anchovy and shrimp. The logarithmic model fitted into the drying data for both anchovy and shrimp with R^2 values of 0.9989 and 0.9998, RMSE values of 0.0016 and 0.0021 and chi-square values of 0.00033 and 0.00047, respectively. Moraes and Pinto [26] reported Midilli model was found to be the accurate model for fluidized bed drying of anchovy. However, variation in the method of drying is associated with differences in moisture ratios and drying rates that exhibit variation in the selection of best-fit models. Dhanushkodi et al. [27] reported that the Henderson and Pabis model as the appropriate fit for convective drying of anchovy. The equation for the best fit Logarithmic model is presented below,

$$MR = \frac{M - Me}{Mo - Me} = 1.06e^{-0.7514t} + 0.0697 \tag{18}$$

where 't' indicates the drying time in hours.

3.3 Effective moisture diffusivity

Effective moisture diffusivity (EMD) values of 1.78×10^{-6} m^2/s and 6.0139×10^{-7} m^2/s were obtained for shrimp and anchovy, respectively during biomass drying. The plot of moisture ratio versus drying time is shown in Fig. 4. The comparatively higher value of EMD for anchovy can be

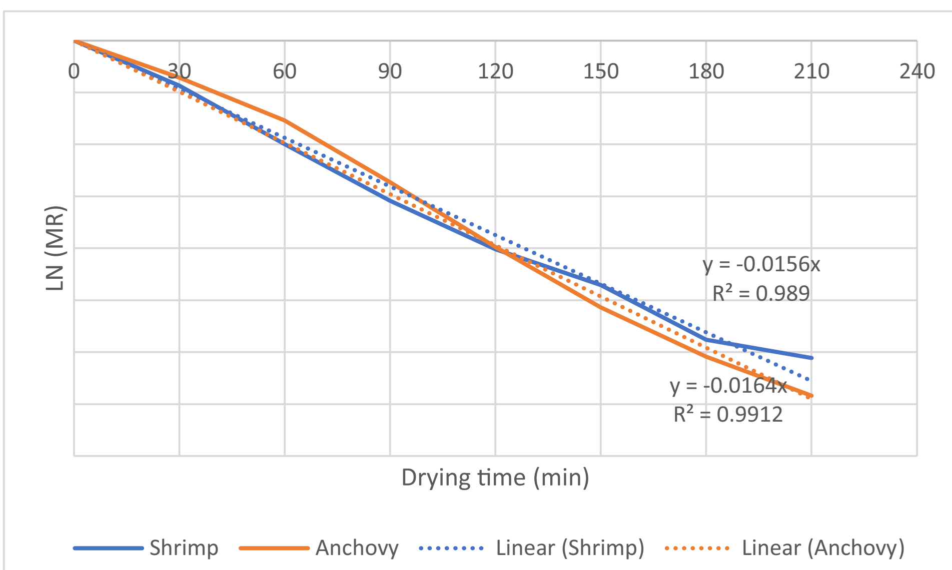

Fig. 4 ln (MR) versus drying time for biomass drying of shrimp and anchovy

attributed to its relatively larger surface area. Alfiya et al. [3] reported EMD values of 6.7×10^{-7} m^2/s for drying shrimp in the forced convection microwave dryer. Murali et al. [5] reported an EMD of 1.04×10^{-9} m^2/s for shrimps in solar hybrid dryers. EMD values are directly related to the velocity of the heating medium and hence influence the rate of drying. The thickness of the products and method shows variation in EMD among various modes of drying.

3.4 Thermal efficiency

The energy efficiency of the biomass dryer is determined as the ratio of the mass of water evaporated to the actual heat energy supplied. Thermal efficiency during biomass drying of anchovy and shrimp was determined to be 21.23% and 24.15%, respectively. The difference in the final dried weight of shrimp and anchovy was found to be the cause for variation in the drying efficiencies. Since biomass drying of both shrimp and anchovy was completed in 3.5 h, fuel consumption remained the same in both cases. Dhanuskode et al. [27] reported a drying efficiency of 9% for biomass drying of cashew nuts to attain moisture reduction from 9 to 4% within 7 h. The lower drying time in the present work might be the reason for an enhanced thermal efficiency.

3.5 Rehydration ratio

The rehydration ratio of shrimp and anchovy was obtained to be 1.8 and 1.6, respectively (Fig. 5). Duan et al. [28] stated the rehydration rate of Tilapia in the range of 2.1–2.5 in the microwave-dryer. Both anchovy and shrimp showed the highest rehydration at the beginning which gradually declined. Poromeric studies have revealed that initially, the pores created by water vapour diffusion absorb the water at rapid rates. During the process of rehydration, an equilibrium is achieved after the gradual slowing down of moisture absorption. Alfiya et al. [29] have reported rehydration ratios of 2.39 and 2.51 for solar and microwave-dried shrimp, respectively. The more the rehydration, the lesser the extent of cell damage during the drying process. Delfiya et al. [4] stated the infrared drying of anchovies results in a rehydration ratio between 2.1 and 2.74.

3.6 Shrinkage

The shrinkage values of biomass dried shrimp and anchovy were obtained as 16.34% and 14.66%, respectively. Shrinkage represented the rate of dimensional deformation on the products during drying. Delfiya et al. [4] also published that the shrinkage of anchovies varied in the range of 17.02–32.61% under infrared drying powers of 1000–3000 W/m^2. However, the higher air velocities from the blower have reduced the drying times in the present study which might have reduced the shrinkage of the dried samples. Murali et al. [5] determined the shrinkage value of solar–LPG dried shrimp to be 13.28%. Controlled drying temperature and airflow rate maintained during the drying process have resulted in quick moisture removal that positively affected the shrinkage of the products. Alfiya et al. [6] observed a shrinkage of 14.14% in the microwave-dried shrimp. Reduction in shrinkage (%) is also an indication of reduction in the case of hardening of dried products. Photographs of anchovy and shrimp before and after biomass drying are shown in Figs. 6 and 7.

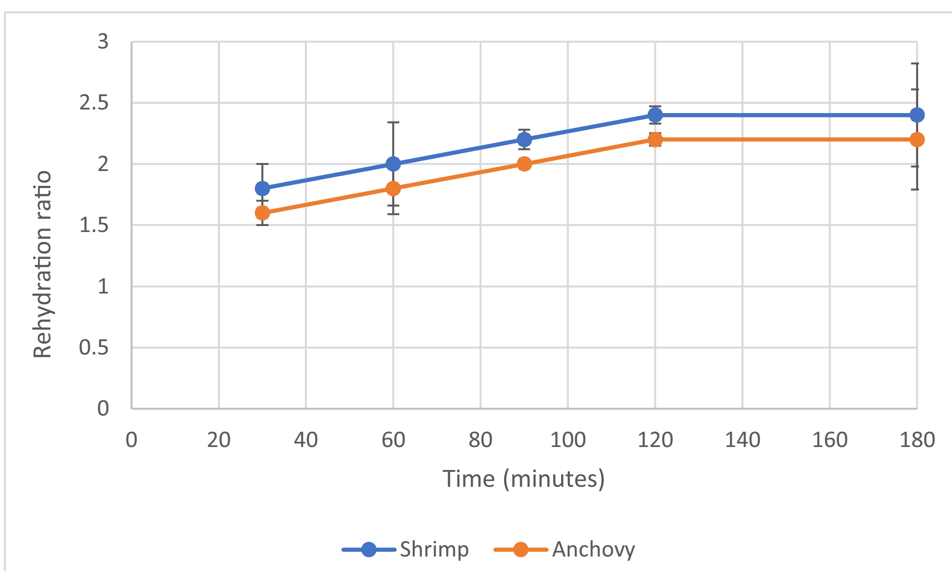

Fig. 5 Rehydration ratio of dried shrimp and anchovy

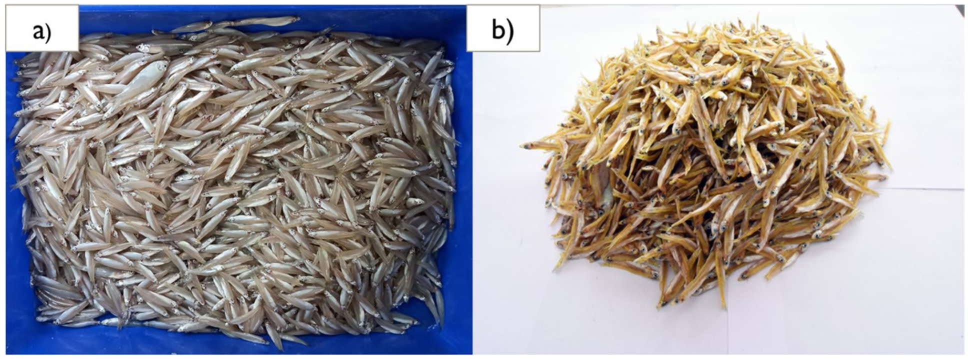

Fig. 6 Photographs of anchovy fresh (**a**) and dried (**b**)

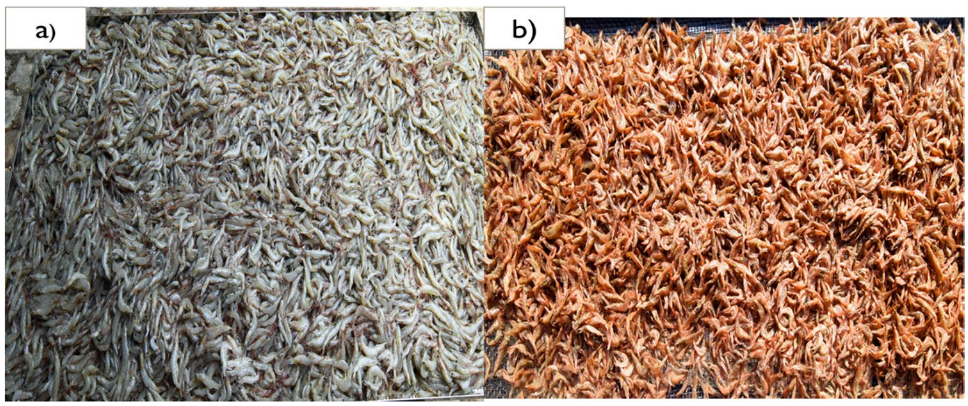

Fig. 7 Photographs of shrimps fresh (**a**) and dried (**b**)

3.7 Exergy analysis

The exergy efficiency of the biomass-fueled convective dryer for anchovy and shrimp was observed to be 38.17 and 34.56%, respectively. The part of the exergy represents useful work that can be extracted from the present drying system. The magnitude of exergy efficiency is dependent on the overall drying and thermal efficiencies. However, the obtained exergy efficiency can be taken as the total of the split exerygy from various components including the biomass combustion unit, heat transmission unit and blower system [30]. The unavoidable technological constraints in the design of the components might be the reason for a part of the exergy destruction in the drying system. Since the designed dryer caters to a maximum of 50 kg loading, an upscaled model may be more effective economically and technologically, as the processing time was found to be the same in both cases. An increase in drying air inlet temperature resulted in a decrease in endogenous exergy as it enhanced the temperature gradient between the drying medium and ambient air. Ndukwu et al. [31] reported exergy efficiency of 19.09 to 52% for solar dryers with natural and forced circulation of air for drying of chilli, potato, plantain and cocoyam. The exergy loss for anchovy and shrimp in the biomass dryer was calculated to be 0.711 and 0.70 kW, respectively. However, the exergy values are more or less the same due to the constant duration of drying for both products. The observations of this study align with the findings of Alfiya and Jayashree [32]. Further, recirculating a fraction of exit air to the drying chamber may enhance the overall efficiency and drying rate as reported by Tippayawong et al. [33]. The distribution of baffles in the airflow passage may also improve the efficiency of the drying system. However, the performance of the present system is efficient when compared with the literature on biomass dryers [34, 35,36]. Table 5 shows the environmental impact analysis of shrimp and anchovy under a biomass drying system.

Table 5 Exergy and environmental impact analysis of biomass dryer for anchovy and shrimp

	Anchovy	Shrimp
Exergy efficiency	38.17%	34.56%
Exergy loss	0.711 kW	0.70 kW
Environmental destruction coefficient	1.62	2.51

3.8 Environmental impact analysis

The sustainability of any drying system is determined by its environmental impact and stability. The energy payback period of the biomass-fueled convective dryer was observed to be 0.27 years, which in turn validates the sustainability of the drying system. The energy payback period of solar dyers was reported to be 0.78 years [37–39]. The sustainability index and environment destruction coefficient of the biomass dryer were observed to be 1.62 and 2.51, respectively. The waste energy ratio, environmental impact factor and improvement potential of the developed dryer were 0.618, 1.69 and 0.4408, respectively. All the values obtained for environmental impact analysis are in line with the findings of Ndukwu et al. [31, 34]. The environmental impact analysis shows that upgrading to multiple renewable energy-based systems for drying can further improve the positive impact on the environment.

3.9 Economic analysis

An economic assessment of biomass dryers for drying shrimp and anchovy was carried out in the present study (Table 6). This method involves determining the annualized cost method, life cycle savings method, payback period and benefit–cost ratio. Table 6 shows the details of assumptions and price values taken for economic analysis and the calculated values for shrimp and anchovy drying using a biomass dryer.

The economic assessment revealed that the production of dried anchovy and shrimp in biomass dryer is economically viable and affordable to fishers. The payback period of 0.58 and 0.70 years was obtained for shrimp and anchovy drying, respectively, and has no associated risk factor. In addition, biomass-based drying systems have the advantage of lower operational costs. The payback period of less than 1 year for both samples was mainly due to the use of biomass energy to supply heat and dry materials, which can significantly reduce or eliminate the need for conventional energy/fuel sources [20]. Sreekumar et al. [39] published that the cost of drying in solar dryers is always lesser than in any other electrical-based drying systems and reported a nominal payback period of 1.5 to 2.1 years depending on the products to be dried. Lingayat et al. [40] studied the techno-economic viability of operating renewable energy-based dryers for pineapple and reported a payback period of 0.54 years. Benefit–cost ratio of more than one for both shrimp (1.85) and anchovy (1.55) drying indicates the economic viability of the newly developed biomass dryer for marine products.

4 Conclusions

A biomass-fueled convective drying unit was designed for marine products and the performance was evaluated using anchovy and shrimps. The moisture content of anchovy decreased from 525 to 17.18% (d. b) in 3.5 h, whereas the moisture content of shrimp decreased from 387 to 18% (d.b) in the same duration. The logarithmic model fitted into the drying data for both anchovy and shrimp. The

Table 6 Considerations for economic analysis of shrimp and anchovy drying in biomass dryer

S. No	Parameters	Shrimp	Anchovy
1	Interest rate (%)	10	
2	Rate of inflation (%)	5	
3	Salvage (%)	10% of the annual capital cost	
4	Maintenance cost (%)	10% of the annual capital cost	
5	Cost of fresh products (INR/kg)	150	200
6	Selling price of dried products (INR/kg)	600	700
7	Annual operation (days)	200	200
8	Capital cost of the dryer (INR)	175,000	175,000
9	Capacity of dryer (kg/day), C_{cc}	30	30
10	Life span of the dryer (years)	20	20
11	Electricity cost (INR/year)	3600	3600
12	Annualized capital cost (INR), C_{ac}	21,000	21,000
13	Labour cost (INR), C_L	100,000	100,000
14	Annualized maintenance cost (INR), C_m	2100	2100
15	Annualized cost of the dryer (INR), C_a	141,658	141,658
16	Unit cost of drying (INR), C_s	70.64	70.64
17	Savings per batch (INR)	1540	1290
18	Annual savings (INR)	323,400	270,900
19	Present worth of annual savings, P_j (INR)	293,971	246,248
20	Payback period (years)	0.58	0.70
21	Benefit–cost ratio	1.85	1.55

rehydration ratio of shrimp and anchovy was 1.8 and 1.6, respectively. The thermal efficiency during biomass drying of anchovy and shrimp was determined to be 21.23% and 24.15%, respectively. The shrinkage values of biomass dried shrimp and anchovy were obtained as 16.34 and 14.66%, respectively, which was within the acceptable limits for both samples. The exergy efficiency of the biomass-fueled convective dryer for anchovy and shrimp was observed to be 38.17 and 34.56%, respectively. The sustainability index, environmental impact factor and improvement potential of the developed dryer were found to be favourable to the biomass drying of both samples. Benefit–cost ratio of more than one for both shrimp (1.85) and anchovy (1.55) drying indicates the economic viability of dryers. The study shows that biomass drying of anchovy and shrimp resulted in hygienically dried superior quality products under reduced drying times. Considering the favourable techno-economic assessment findings of the biomass dryer, it can be recommended for extensive drying of marine products. The efficiency, energy and exergy values in the investigations can be attributed to the losses associated with the different components. The limitations of the study are no temperature control of drying air and manual feeding of biomass to the furnace. Further research can be in line of standardising the drying conditions for other fish and shellfish products. On design aspects, provision for baffles in the hot air may be introduced to enhance the rate of heat transfer by creating turbulence in the airflow pattern. Also, multiple renewable energy-based systems, viz., solar-biomass dryers can further enhance the efficiencies with lesser environmental impacts.

Abbreviations D_{eff}: Effective diffusivity (m^2/s); B: Shape factor; C_p: Specific heat of air (kJ/kg °C); D_{Final}: Geometric mean diameter of the dried samples (m); $D_{Initial}$: Geometric mean diameter of fresh samples (m); *DR*: Rate of drying (g/g dm. h); L: Latent heat of vaporization water (kJ/kg); M_t: Moisture content at time (t = t); M_{t+dt}: Moisture content at time (t + dt); m_a: Mass of air (kg); M_d: Moisture content (%), (d.b); M_e: Equilibrium moisture content (%); M_f: Final moisture content (%), (w. b); M_i: Initial moisture content (%), (w. b); M_o: Moisture content at time (t = o); *MR*: Moisture ratio; M_w: Amount of water removal (kg); r: Radius (m); T_f: Temperature of air at the outlet,, (°C); T_i: Temperature of air at the inlet,, (°C); W_F: Sample weight at the end of drying (g); W_I: Sample weight before drying (g); W_i: Initial product weight (g)

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Data availability The authors confirm that the data supporting the findings of this study are available with the authors and will be made available upon reasonable request.

Declarations

Ethical approval Not applicable.

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References

1. Murali S, Delfiya DA, Alfiya PV, Samuel MP, Ninan G (2023) Development of sensible heat storage based solar hybrid dryer with evacuated tube collector and biomass gasifier for shrimp drying. Sol Energy 262:111836
2. Mishra L, Hauchhum L, Gupta R (2022) Development and performance investigation of a novel solar-biomass hybrid dryer. Appl Therm Eng 211:118492
3. Alfiya PV, Rajesh GK, Murali S, Delfiya DA, Samuel MP, Prince MV (2022) Quality evaluation of solar and microwave dried shrimps–a comparative study on renewable and dielectric heating methods. Sol Energy 246:234–244
4. Aniesrani Delfiya DS, Sneha R, Prashob K, Murali S, Alfiya PV, Samuel MP (2022) Hot air-assisted continuous infrared dryer for anchovy fish drying. J Food Process Eng 45(6):e13824
5. Murali S, Delfiya DA, Kumar KS, Kumar LR, Nilavan SE, Amulya PR, Krishnan VS, Alfiya PV, Samuel MP (2021) Mathematical modeling of drying kinetics and quality characteristics of shrimps dried under a solar–LPG hybrid dryer. J Aquat Food Prod Technol 30(5):561–578
6. Alfiya PV, Rajesh GK, Murali S, Aniesrani Delfiya DS, Samuel MP, Prince MV (2022) Development and evaluation of hot air-assisted microwave dryer for shrimp (*Metapenaeus dobsoni*). J Food Process Preserv 46(11):e17112
7. Lauri P, Havlík P, Kindermann G, Forsell N, Böttcher H, Obersteiner M (2014) Woody biomass energy potential in 2050. Energy Policy 66:19–31
8. Rizal TA, Muhammad Z (2018) Fabrication and testing of hybrid solar-biomass dryer for drying fish. Case Studi Therm Eng 12:489–496
9. Yuwana Y, Sidebang B (2016) Performance testing of the hybrid solar-biomass dryer for fish drying. Int J Mod Eng Res 6(11):63–68
10. Chavan BR, Yakupitiyage A, Kumar S (2008) Mathematical modeling of drying characteristics of Indian mackerel (*Rastrilliger kangurta*) in solar-biomass hybrid cabinet dryer. Drying Technol 26(12):1552–1562
11. Murali S, Aniesrani Delfiya DS, Sajesh VK, Neethu KC, Sathish Kumar K, & Ninan G (2024) Experimental evaluation of biomass gasifier integrated solar hybrid dryer using shrimps: gasifier performance, modeling of drying behavior, and quality analysis. Biomass Convers Biorefinery 1–13. https://doi.org/10.1007/s13399-024-05395-7
12. Zarein M, Samadi SH, Ghobadian B (2013) Investigation of microwave dryer effect on energy efficiency during drying of apple slices. J Saudi Soc Agric Sci. https://doi.org/10.1016/j.jssas.2013.06.002
13. Montero I, Blanco J, Miranda T, Rojas S, Celma AR (2010) Design, construction and performance testing of a solar dryer for agroindustrial by-products. Energy Convers Manage 51:1510–1521
14. Murali S, Amulya PR, Alfiya PV, Delfiya DA, Samuel MP (2020) Design and performance evaluation of solar-LPG hybrid dryer for drying of shrimps. Renew Energy 147:2417–2428
15. Prasad J, Vijay VK (2005) Experimental studies on drying of Zingiber officinale, Curcuma longa I and Tinospora cordifolia in solar–biomass hybrid drier. Renew Energy 30(14):2097–2109

16. Mugi VR, Chandramohan VP (2021) Energy, exergy and economic analysis of an indirect type solar dryer using green chilli: a comparative assessment of forced and natural convection. Therm Sci Eng Progr 24:100950
17. Ståhl M, Granström K, Berghel J, Renström R (2004) Industrial processes for biomass drying and their effects on the quality properties of wood pellets. Biomass Bioenerg 27(6):621–628
18. Youcef-Ali S, Messaoudi H, Desmons JY, Abene A, Le Ray M (2001) Determination of the average coefficient of internal moisture transfer during the drying of a thin bed of potato slices. J Food Eng 48(2):95–101
19. Doymaz İ, İsmail O (2011) Drying characteristics of sweet cherry. Food Bioprod Process 89(1):31–38
20. Philip N, Duraipandi S, Sreekumar A (2022) Techno-economic analysis of greenhouse solar dryer for drying agricultural produce. Renew Energy 199:613–627
21. Dutta P, Dutta PP, Kalita P (2021) Thermal performance studies for drying of Garcinia pedunculata in a free convection corrugated type of solar dryer. Renew Energy 163:599–612
22. Ferrari A, Gutiérrez S, & Sin G (2015) A comprehensive sensitivity and uncertainty analysis of a milk drying process. In: Computer Aided Chemical Engineering. Elsevier, Vol. 37, pp 2225–2230. https://doi.org/10.1016/B978-0-444-63576-1.50065-0
23. Dongbang W, Pirompugd W (2015) Experimental study on drying kinetics of anchovy using centrifugal fluidized bed technique. Int J Agric Biol Eng 8(5):132–141
24. Shalini J, Samsher SC, Kumar V, Chauhan N, Yadav MK (2017) Effect of moisture content and drying rate on dried aonla shreds during ambient storage. IJCS 5(4):362–366
25. Jain D, Pathare PB (2007) Study the drying kinetics of open sun drying of fish. J Food Eng 78(4):1315–9
26. Moraes KD, Pinto LADA (2013) Drying kinetics, biochemical and functional properties of products in convective drying of anchovy (*Engraulis anchoita*) fillets. Int J Food Eng 9(4):341–351
27. Dhanushkodi S, Wilson VH, Sudhakar K (2015) Design and performance evaluation of biomass dryer for cashewnut processing. Adv Appl Sci Res 6(8):101–111
28. Duan ZH, Jiang LN, Wang JL, Yu XY, Wang T (2011) Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. Food Bioprod Process 89(4):472–476
29. Alfiya PV, Murali S, Delfiya DA, Sreelakshmi KR, Sivaraman GK, Ninan G (2022) Kinetics, modelling and evaluation of Bombay duck (*Harpodon nehereus*) dried in solar-LPG hybrid dryer. Sol Energy 242:70–78
30. Edgars V, Girts V, Ivars V, Dace L, Krista K, Blumberga D (2015) Analysis of energy consumption for biomass drying process. Environ Technol Resources 2:317–322
31. Ndukwu MC, Ibeh MI, Etim P, Augustine CU, Ekop IE, Leonard A, Bennamoun L (2022) Assessment of eco-thermal sustainability potential of a cluster of low-cost solar dryer designs based on exergetic sustainability indicators and earned carbon credit. Clean Energy Syst 3:100027
32. Alfiya PV, Jayashree E (2024) Solar-biomass and dielectric drying of mace: an investigation on renewable and fourth generation drying technologies. Sol Energy 277:112717
33. Tippayawong N, Tantakitti C, Thavornun S, Peerawanitkul V (2009) Energy conservation in drying of peeled longan by forced convection and hot air recirculation. Biosys Eng 104(2):199–204
34. Ndukwu MC, Bassey B, Okon FI, Abam B, Lamrani N, Bekkioui H, Wu L, Bennamoun U, Egwu CN, Ezewuisi CB, Ndukwe C, Nwachukwu J, Ehiem C (2022) Energy and exergy analysis of solar dryer with triple air passage direction collector powered by a wind generator. Int J Energy Environ Eng https://doi.org/10.1007/s40095-022-00502-8
35. Lokras S (2012) Development and dissemination of fuel-efficient biomass burning devices. J Indian Inst Sci 92(1):99–110
36. Anju K, Sudhakar K (2014) Study on performance evaluation of biomass drier for Green chili (*Capsicum annuum L.*). Second National Conference on Power Electronics in Sustainable Energy Development. Bonfring, India, pp 135–139
37. Erbay Z, Hepbasli A (2013) Advanced exergy analysis of a heat pump drying system used in food drying. Drying Technol 31(7):802–810
38. Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science 360(6392):987–992
39. Sreekumar A (2010) Techno-economic analysis of a roof-integrated solar air heating system for drying fruit and vegetables. Energy Conver Manage 51(11):2230–2238
40. Lingayat A, Balijepalli R, Chandramohan VP (2021) Applications of solar energy based drying technologies in various industries–a review. Sol Energy 229:52–68