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Environmental, economic and quality assessment of hybrid solar-electric drying of black soldier fly (*Hermetia illucens*) larvae

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A R T I C L E I N F O

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A B S T R A C T

The exploration of insects as a sustainable protein source is gaining interest as an alternative solution to ensure food security and meet the increasing global food demand. Black Soldier Fly (*Hermetia illucens*) Larvae (BSFL) present a natural and sustainable protein source for both feed and food applications. In the process of incorporating them into feed and food products, larvae typically undergo a drying stage as the initial step. This research aims to delve into the Hybrid Solar-Electrical Drying (HSED) of BSFL at four different temperatures: 40, 50, 60, and 70 °C. The energy payback time for the dryer is determined to be 1.57 ± 0.09 years, with CO_2 emissions measuring 72.58 ± 2.90 kg CO_2/year and a net CO_2 mitigation of 57.19 ± 2.35 tons over its lifespan, highlighting its environmentally friendly nature. The proposed HSED system exhibits a remarkably short payback period of only 0.71 years. Furthermore, the dryer has the potential to save up to 1496.04 USD annually, emphasizing its economic efficiency and financial benefits. The larvae dried using the HSED have a protein content ranging from 38.14 ± 0.28% to 42.33 ± 0.12% exceeding the minimum requirement of 34% set by leading companies in the insect production market. This makes them highly competitive in the market. Furthermore, the dried larvae produced with this hybrid dryer exhibit superior quality compared to conventional drying methods, specifically in terms of protein content, with a margin of 7.08%.

1. Introduction

Insects have become a sustainable source of food and feed, owing to their high protein content and interesting composition of healthy fats, minerals, and vitamins [1]. Among these, the larva of the black soldier fly (*Hermetia illucens* L.) (BSFL) stands out as one of the most promising insects, given its sustainable and ecological farming system and its capacity for the bioconversion of organic waste into high-quality nutrients, particularly proteins, highlighting its potential to play a pivotal role in contributing to a circular economy [2]. BSFL serves as an alternative to traditional protein sources, allowing for the production of protein-rich flours intended for inclusion in animal feed, especially in aquaculture, as well as in human food or as a functional ingredient [3,4]. Furthermore, its versatility extends beyond the realm of animal nutrition. These larvae have the capability to generate a diverse array of valuable by-products, including lipids for biodiesel production [5] and cosmetics [6], biofertilizer for agricultural practices [7], and chitin for pharmaceutical and medical applications [8].

While fresh larvae can be utilized to feed animals, the challenge of storage, conservation, and limited lifespan becomes apparent on a large scale, primarily attributed to their high water content. Hence, there is a need to dry the larvae. Solar drying is one of the oldest and most widely used methods of drying insects [9]. The solar dryer enables the heating and dehumidification of the product through an instantaneous transfer of mass and heat by the hot air. This method not only improves the quality of the dried product but also reduces production costs while

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preventing the emission of greenhouse gases that can negatively influence the global environment. Solar dryers commonly face challenges associated with their reliability and the intermittent nature of weather conditions. These challenges become evident in the inconsistent quality of sunlight radiation during cloudy days and rainy periods and the absence of sunlight during night time. Hybridization addresses these issues by allowing the drying process to persist during off sunshine hours, drawing on backup energy from stored heat and/or an alternative energy source [10]. This ensures that the product is shielded from potential deterioration due to microbial invasion, thereby enhancing the sanitary quality of both the drying process and the final product [9].

Hybrid solar dryers are systems that utilize solar energy in conjunction with another heating source, such as biomass, electric heaters or fossil fuels, to heat the drying air [11]. This is done to ensure continuous drying operations irrespective of weather conditions. Additionally, they enable the control of the drying chamber's aerothermal conditions, encompassing temperature, humidity, and air velocity. Consequently, these hybrid systems allow meticulous control over the drying kinetics and the quality of the dried product [12].

Kushwah et al. [13] investigated experimentally the thermal performance of a greenhouse dryer with heat exchanger incorporated with evacuated water tube collector. By using the hybrid greenhouse solar dryer, the drying time was reduced by 30% compared to open sun drying. Abedini et al. [14] evaluated the performance of a cabinet hybrid solar-infrared dryer used for drying shrimp. With a maximum capacity of 2,5 kg, the hybrid drying system's average thermal efficiency reached 16.37%. Atalay et al. [15] studied the energy and exergy analysis of a solar-wind energy assisted hybrid dryer for drying banana slices. The exergy efficiency of the hybrid system exhibited a range from 68.04% to 83.89%. Significantly, the hybrid dryer surpassed the exergy efficiency of other conventional solar dryers by an impressive margin of 57.7%. The dryer was determined to be both economical and environmentally friendly, as it relies solely on two renewable energy sources, demonstrating an energy payback period of 1.36 years. Abdenouri et al. [16] examined the thermal behaviour of an indirect hybrid solar-electric dryer for agriproducts drying. The temperature controller enabled a reduction of 11.3% in conventional energy consumption for continuous use throughout both day and night. Nwakuba et al. [17] designed a solar dryer equipped with an electric heater for drying red pepper, evaluating its overall performances and suitability. Various drying temperatures (50, 60, and 70 °C) and air velocities (1.14, 2.29, and 3.43 m/s) were investigated. The hybrid dryer exhibited an energy efficiency ranging from 13.2% to 35.6%. The maximum exergy efficiency was noted at the lowest air velocity of 1.14 m/s and the lowest drying temperature of 50 °C. Remarkably, the developed dryer achieved a 30.3% higher reduction in CO_2 emissions compared to a hybrid solar-biomass dryer under similar climatic conditions. Singh and Gaur [18] developed a hybrid active greenhouse solar dryer incorporating an evacuated solar collector for the dehydration of high-moisture agricultural products. An assessment of the environmental and economic aspects of this hybrid system was conducted, focusing on the drying of tomato slices. The resulting dryer has the capacity to yield 261 kg of dried tomato annually, with a remarkably short payback time of only 1.73 years in comparison to its 30-year lifespan. Over its entire operational life, the dryer is expected to mitigate 169.10 tonnes of CO_2 emissions, underscoring its suitability from a sustainable perspective. The review of the aforementioned papers confirms the substantial impact of hybrid solar dryers in improving drying kinetics and enhancing energy and exergy efficiency. Additionally, these dryers demonstrate sustainability both environmentally and economically.

BSFL drying has been studied in the literature using different techniques. Monisha et al. [19] conducted a study to assess the influence of freeze-drying and direct solar drying on the quality of defatted black soldier fly larvae (BSFL) flour. The results revealed that freeze-drying yielded flour with a high-quality protein content of 44.63%, exhibiting greater stability during storage compared to flour obtained through direct solar drying (39.74%). This underscores the advantage of utilizing freeze-dried defatted flour as a functional ingredient. However, it is important to note that freeze-drying is a more expensive technique compared to traditional solar drying, making it less adaptable on an industrial scale. Purnamasari et al. [20] investigated the nutrient composition of BSFL under varying growth media (fruit pulp, cassava peel, food scraps and tofu waste), temperature conditions (55 °C, 65 °C and 75 °C), and drying times (24h and 36h), employing an oven dryer. The nutritional quality of the larvae was influenced by the various factors under investigation. The larvae had the highest protein content (50.65%) when cultivated in tofu waste and subjected to drying at 55 °C for 24 h. Huang et al. [21] examined the influence of conventional drying at 60 °C and microwave drying on the quality of BSFL proteins. The larvae dried using oven drying exhibited superior protein digestibility and higher digestible indispensable amino acid score compared to those dried using the microwave. Consequently, larvae dried through conventional drying method can be considered a valuable source of animal protein. Saucier et al. [22] conducted a comparative analysis, examining the impact of drying black soldier fly larvae (BSFL) through forced convection at 60 °C and freeze-drying on their quality. Hot air drying proved to be significantly faster, up to 6 times, compared to freeze-drying, resulting in a protein content of 40.0%, while freeze-dried larvae exhibited a slightly lower protein content of 38.5%. However, hot-air drying exhibited the most substantial colour change and oxidation levels compared to freeze-drying.

Following our bibliographic review and considering our current knowledge, a research gap is evident in the field of hybrid solar drying of BSFL. Our primary objective is to investigate this process with the aim of producing dried larvae on an industrial scale, employing an innovative, environmentally friendly, and economically viable method. The ultimate goal is to ensure a high-quality product that is competitive in the market, all while prioritizing environmentally respectful production processes and economic sustainability.

In this study we will experimentally evaluate the performance of a hybrid solar-electrical dryer for drying BSFL. This evaluation encompasses assessing the drying kinetics, the environmental impact, the economic viability of the developed system, and the nutritional and physicochemical quality of dried larvae with the aim of integrating this system into large-scale larvae production units.

2. Method and materials

2.1. Materials

Black soldier fly larvae (BSFL), aged 13 days, were sourced from the start-up "EntomoNutris"(Fig. 1). They were meticulously washed with

Fig. 1. Live black soldier fly larvae.

tap water, and subsequently killed by blanching at 100 °C for 40 s [23] (Fig. 2). For each experimental trial, 1 kg of blanched BSFL underwent drying processes utilizing a hybrid solar-electrical dryer (HSED) at four distinct temperatures: 40, 50, 60, and 70 °C. The drying process continued until the larvae reached a final moisture content ranging between 14% and 10%. The HSED was carefully operated to prioritize solar energy utilization. In instances where the solar input fell short of achieving the target temperature, an electrical resistor (2 kW) was activated to supplement the temperature. To regulate the drying chamber's temperature, a PID controller (proportional–integral–derivative controller) was synthesized through the identification and modeling of our system. When a temperature differential emerged between the user-set temperature and the actual temperature inside the dryer, the controller issued a control signal to the electric heater, elevating the temperature to the desired level. At each temperature setting, three samples of larvae (20 g each) were considered, and their moisture content was measured at brief intervals, ensuring a detailed understanding of the drying kinetics.

The HSED utilized in this study (Fig. 3) incorporates several components for efficient operation. Notably, it features an electrical resistance heater positioned between the outlet collector and the chamber's inlet, boasting a maximum power capacity of 4 kW. The system includes a solar collector with a surface area of 2 m^2 ($A_{collector} = 2$ m^2), a cubic drying chamber measuring 1 m × 1 m x 1 m, equipped with four mesh trays totalling a surface area of 0.98 m^2. Atop the drying chamber sits an electric fan of 10 cm diameter. The solar collector is strategically fixed at a 30° tilt to the south-facing horizontal. To monitor the conditions within the drying chamber, the relative humidity and temperature of the dryer air are gauged using HM-110 probes (with 0.5% accuracy) and TM-110 pt100 probes (with 0.5 °C accuracy), respectively. Additionally, the air's temperature and wind velocity are recorded by a Vantage Pro2 meteorological station (ref. 6162CFR).

The operational mechanism of the HSED is outlined as follows: In the initial phase, the incoming air to the solar collector undergoes heating facilitated by the absorbent plate and the greenhouse effect induced by the solar intensity interacting with the glass cover. Subsequently, this heated air reaches the inlet of the drying chamber with a variable temperature. Within the chamber, an auxiliary heating system is employed to further elevate the air temperature, ensuring precise control to meet the desired drying conditions. Following this, the dried air is efficiently extracted by the exhaust fan, the speed of which can be finely controlled by adjusting the electric power supplied to the fan.

Fig. 2. Blanched black soldier fly larvae.

The dryer boasts a manufacturer-stated lifespan of 25 ± 1.00 years, a result of meticulous choices in construction materials, construction methods, and the extensive career experience of the builder in dryer manufacturing. Crafted with precision, it incorporates sustainable, high-quality materials, underscoring the manufacturer's dedication to both durability and environmental consciousness.

As shown in Table 1, four experiments on hybrid solar-electrical drying of BSFL were conducted at temperatures of 40, 50, 60, and 70 °C under non-controlled natural ventilation conditions, a configuration in which ventilation energy is almost negligible, which represents the favorable case in terms of energy consumption.

The solution methodology diagram for hybrid solar-electrical drying of BSFL is illustrated in Fig. 4. The drying kinetics and analysis methods (economic, environmental, and quality analysis) are depicted as parameters to be determined based on the equations mentioned.

2.2. *Drying kinetics*

The drying kinetics and diffusional stage of solar drying for BSFL were thoroughly investigated and discussed in the present study. The analysis of moisture content variation (X_t) during experiments is conducted based on three distinct drying periods: the warming-up phase, the falling period, and the paradoxical stage. Subsequently, the discussion revolves around the moisture ratio (*MR*) and drying rate (*DR*) in relation to drying time and moisture variation. The variables M_t (moisture content in g water/g dry matter), *MR* (moisture ratio in %), and *DR* (drying rate in g water/g dry matter. h) are defined as per Eqs. (1)–(3), respectively.

$$M_t = \frac{m_t - m_d}{m_d} \tag{1}$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{2}$$

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{3}$$

Where (m_t), (m_d), (M_0), and (M_e) represent the mass of BSFL at a given time (g), the mass of dried larvae, initial moisture content, and equilibrium moisture content, respectively.

2.3. *Environmental analysis*

Environmental analysis is in growing demand for evaluating the environmental impact of dryers and validating their potential industrial applications. Crucial parameters in this evaluation encompass the embodied energy payback period, carbon emissions, and credits. This paper focuses on environmental analysis, specifically for drying BSFL at a temperature of 60 °C using natural convection in a HSED (hybrid mode).

2.3.1. *Embodied energy*

The embodied energy (E_m) of an industrial system refers to the energy, measured in (kWh), necessary to produce 1 kg of the material used in its construction (iron, glass, steel sheet, copper, plastic, paint, fittings, etc.).

2.3.2. *Energy payback time (EPBT)*

The term "energy payback time" (EPBT) is employed to denote the duration (years) required to recover the embodied energy of the dryer. To determine the EPBT using the hybrid mode, two tests at 60 °C were conducted. The first test involved the utilization of 100% solar energy, while the second test employed 100% electric energy, while adjusting the fan to maintain 60 °C in both cases. In each case, the amount of water evaporated (*ME*) was determined. Subsequently, the proportion of each mode in our hybrid mode operation will be taken into consideration.

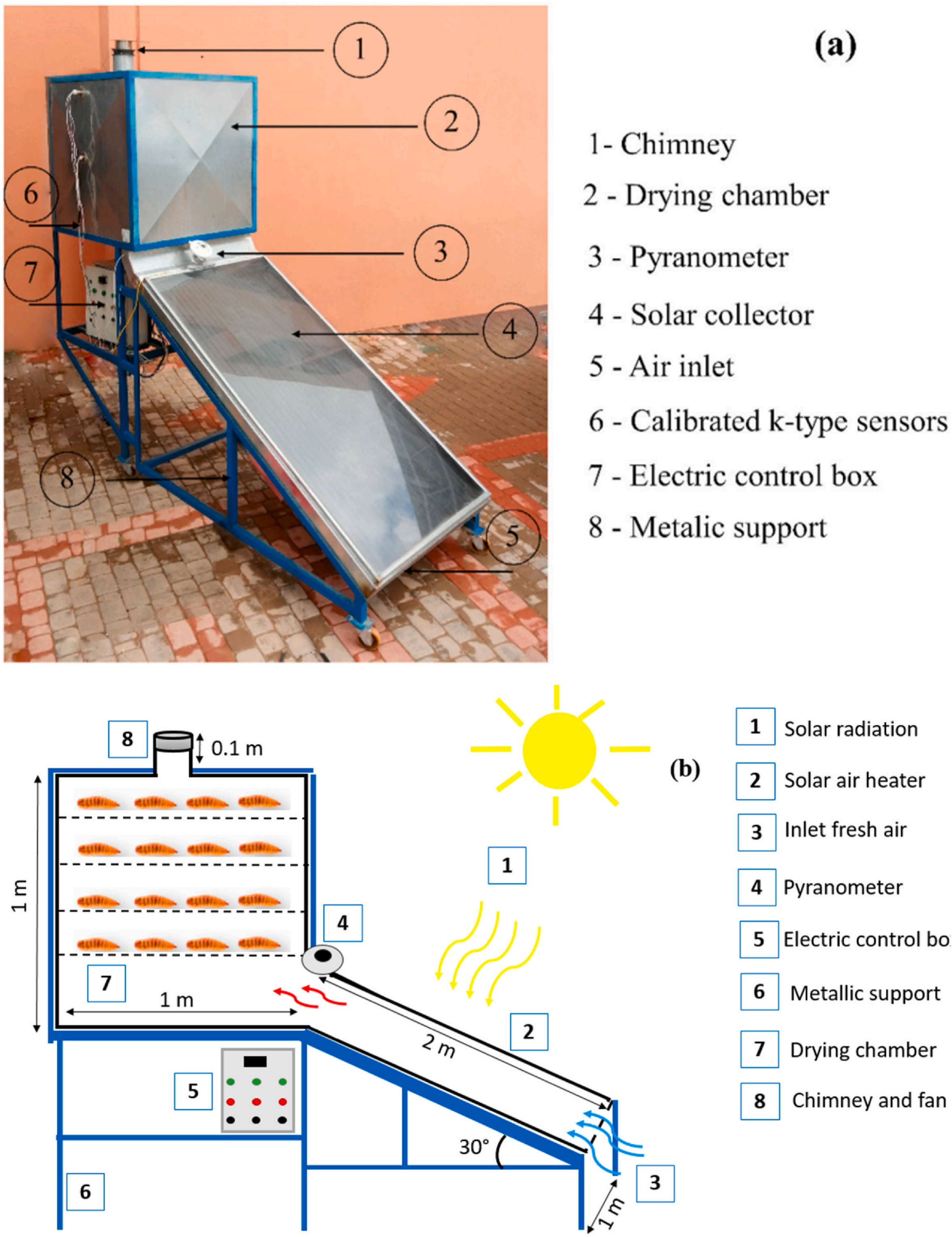

Fig. 3. (a) Real picture of the dryer, (b) 2D schematic of the hybrid solar-electrical dryer.

Eqs. (4)–(12) were used to calculate EPBT:

$$EPBT_{hybrid\ mode} = EPBT_{solar\ mode} + EPBT_{electric\ mode} \tag{4}$$

$$EPBT_{hybrid\ mode} = \frac{S * \frac{E_m}{Eaout,sol} + E * \frac{E_m}{Eaout,elec}}{S + E} \tag{5}$$

$$E_{aout,sol} = \frac{ME_{sol} \times L_{vap}}{3.6 \times 10^6} \times N_{sd} \tag{6}$$

$$E_{aout,elec} = \frac{ME_{elec} \times L_{vap}}{3.6 \times 10^6} \times N_{sd} \tag{7}$$

$$ME = \frac{(Mi - Mf)}{(100 - Mf)} * mi \tag{8}$$

Table 1
Experimental conditions of drying black soldier fly larvae using the hybrid solar-electrical dryer.

Test	Ambient temperature (°C)	Ambient relative humidity (%)	Relative humidity in the drying chamber (%)	Temperature in the drying chamber (°C)	Drying time (h)
1	25 °C	35%	17.37	40	21
2	25 °C	35%	14.86	50	16
3	27 °C	26%	13	60	6
4	30 °C	29%	7.14	70	2

$$S = \frac{Solar\ energy\ consumed}{Total\ energy\ consumed} * 100\% \tag{9}$$

$$E = \frac{Electrical\ energy\ consumed}{Total\ energy\ consumed} * 100\% \tag{10}$$

$$Solar\ energy\ consumed = Solar\ radiation * t_{solar} * A_{collector} \tag{11}$$

$$Electrical\ energy\ consumed = Resistor\ Power * t_{electric} \tag{12}$$

Where E_{aout} is defined as the annual energy output (kWh/year), S and E are the proportion of solar and electrical energy consumed during the hybrid drying operation at 60 °C, respectively. L_{vap} denotes the latent heat of vaporization ($L_{vap} = 2.26.10^6$ J/kg), and N_{sd} corresponds to the total number of sunshine days in a year, approximately 300 days.

According to the experimentation, it has been determined that the moisture content evaporated (*ME*) using 100% solar energy is 6.21 ± 0.87 kg, and the moisture content evaporated using 100% electrical energy is 6.72 ± 0.27 kg. This process is carried out to achieve a final moisture (M_f) within the range of 14%–10%, utilizing an initial mass (m_i) of BSFL before drying of 11 kg having an initial moisture content (M_i) of 63 ± 0.10 %.

To ascertain the solar and electrical energy consumption during the hybrid mode, the drying at 60 °C involved an average ambient temperature and solar radiation of 22.2 °C and 530W/m^2, respectively. Throughout this test, the dryer achieved a temperature of 55 °C during the 4-h solar-only operation (t_{solar} = 4h). The desired temperature of 60 °C was subsequently reached by employing the electrical resistor, utilizing a 250W power rating for 2 h ($t_{electric}$ = 2h).

2.3.3. Carbone dioxide emission from the dryer

The CO_2 emissions per year from a dryer refers to the total amount of

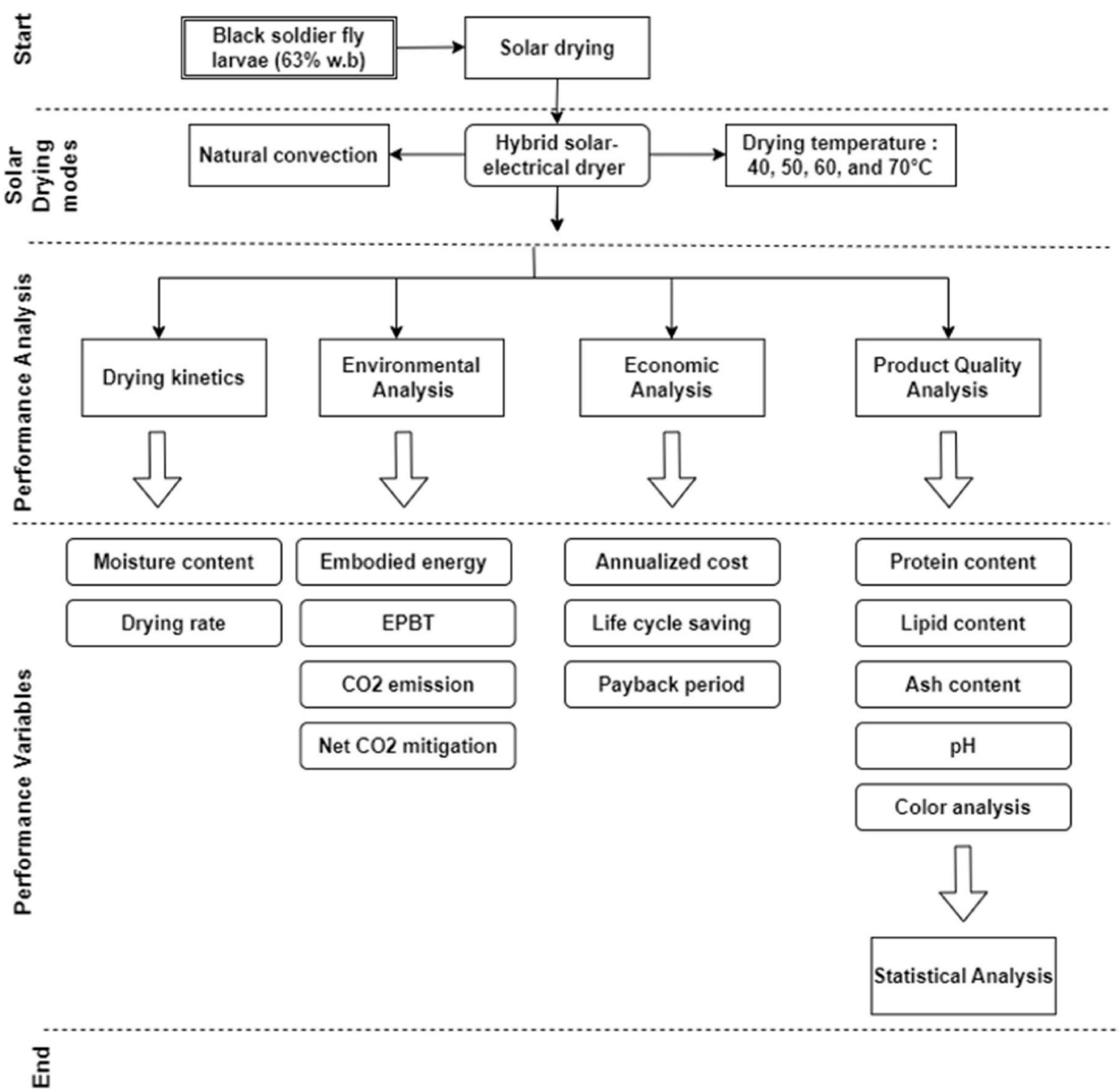

Fig. 4. Block diagram representation of the experimental methodology.

carbon dioxide released into the atmosphere annually as a result of the dryer's operation. This includes emissions generated directly by the dryer's energy consumption, as well as any indirect emissions associated with the production and supply of the energy sources it utilizes. The average CO_2 emission for electricity generated from coal is approximately 0.98 kg CO_2/kWh [24]. The CO_2 emission per year can be estimated using Eq. (13):

$$CO_2 emission\ per\ year = \frac{E_m \times 0.98}{n} \tag{13}$$

The lifetime of the HSED (n) is approximately 25 ± 1.00 years according to the constructor.

2.3.4. Carbone dioxide mitigation

The primary criterion for evaluating climate change impact is the mitigation of carbon dioxide in (kWh). Taking into account losses incurred during transmission and distribution ($L_{td} = 45\%$) and domestic appliance losses ($L_a = 10\%$), the amount of CO_2 mitigation of the solar drying system (X) is subsequently determined as follows [25]:

$$X = \frac{1}{1 - L_{td}} \times \frac{1}{1 - L_a} \times 0.98 \approx 2kg \tag{14}$$

$$CO_2 mitigation = E_m \times X \tag{15}$$

$$Net\ CO_2\ mitigation = CO_2\ mitigation - CO_2\ emission = E_{aout} \times X \times n - E_m \tag{16}$$

2.3.5. Carbon credit earned by dryer

One carbon credit is equivalent to mitigating one ton of CO_2 emissions. The earned carbon credits (ECC) can be calculated based on the net lifetime CO_2 mitigation of the dryer system by multiplying the value with the cost of carbon credits (denoted as D), which varies between 5 and 20 USD per ton of CO_2 [26], as depicted in Eq. (17):

$$ECC = Net\ CO_2\ mitigation\ over\ lifetime * D \tag{17}$$

2.4. Economic analysis

The economic analysis of a drying system enables the determination of the necessary investment, the time required to recoup the investment cost, and the estimation of the transition from laboratory scale to industrial application. The key criteria considered in the current economic analysis include the annualized cost, life cycle savings, and the payback period. This analysis was conducted based on the socio-economic status in Morocco.

2.4.1. Annualized cost method

The annualized cost (AC) in (USD) of a dryer system encompasses the annual expenses for operation (C_{acc}), maintenance (C_{mc}), running electricity costs for operation (C_{rec}), and annual salvage value (S_a), which collectively sustain the drying system throughout its lifespan. It can be calculated as follows:

$$AC = C_{acc} + C_{mc} + C_{rec} - S_a \tag{18}$$

Eqs. (19)–(21) are utilized for the determination of the annualized capital cost (C_{acc}) and the salvage value (S_a). The interest rate (i) and inflation rate (r) are consistently set at 2% and 8%, respectively, in accordance with the current rates applicable to Moroccan banks.

$$C_{acc} = C_{ccd} \times \frac{i(1+i)^n}{(1+i)^n - 1} \tag{19}$$

$$S_a = S \times \frac{i}{(1+i)^n - 1} \tag{20}$$

$$S = 10\% \times C_{ccd} \tag{21}$$

Where C_{ccd} and S (in USD) represent the capital cost and salvage value of the HSED, respectively, and n is the lifetime of the dryer.

By addinng the electricity consumed by both the fan ($C_{rec,fan}$) and the electrical resistance ($C_{rec,\ resistance}$), the annual electricity cost (C_{rec}) required to operate the dryer can be estimated as indicated in Eqs. (22)–(24):

$$C_{rec} = C_{rec,fan} + C_{rec,resistance} \tag{22}$$

$$C_{rec,fan} = C_{ee} * W_p * t \tag{23}$$

$$C_{rec,resistance} = C_{ee} * P_h * t \tag{24}$$

The unit price of electricity in Morocco (C_{ee}) is 0.109 USD/kWh. W_p represents the rated power consumption of the fan, and P_h denotes the electric resistance power (2 kWh).

The cost of drying per kg of dried BSFL (CD_{kg}) is calculated using Eqs. (25) and (26):

$$CD_{kg} = \frac{AC}{M_{year}} \tag{25}$$

$$M_{year} = \frac{M_{dry} * D_{year}}{D_b} \tag{26}$$

Where M_{year} and M_{dry} represent the mass of the dried product (kg) per year and per batch, respectively. D_{year} and D_b denote the number of days using the HSED per year and per batch, respectively.

2.4.2. Life cycle savings

The cost per kilogram of the dried larvae (C_{dry}) is determined by multiplying the cost of the fresh larvae (C_{fre}) with the ratio of the fresh mass intended for solar drying (M_{fre}) to the mass of the dried larvae obtained from the dryer (M_{dry}). It is defined by Eq. (27):

$$C_{dry} = \frac{C_{fre} * M_{fre}}{M_{dry}} \tag{27}$$

The cost of dried larvae per kilogram (C_{drys}) is determined by adding the cost of the larvae before drying (C_{dry}) to the cost of 1 kg of the dried larvae (CD_{kg}). The calculation for (C_{drys}) is as follows:

$$C_{drys} = C_{dry} + CD_{kg} \tag{28}$$

The savings per kilogram annually (B_{kg}), per batch (B_b), and per drying day (B_d) in USD are calculated using Eqs. (29)–(31):

$$B_{kg} = C_{bdp} - C_{drys} \tag{29}$$

$$B_b = B_{kg} * M_{dry} \tag{30}$$

$$B_d = \frac{B_b}{D_b} \tag{31}$$

where C_{bdp}, M_{dry}, and D_b represent the cost of selling 1 kg of dried larvae (in USD), the cost per kilogram of dried larvae (in USD), and the number of drying days per batch, respectively.

Therefore, the annual savings (B_j) over the duration of use per year (D_{year}) throughout the lifetime of the drying systems can be defined using Eq. (32):

$$B_j = B_d * D_{year} * (1+r)^{j-1} \tag{32}$$

2.5. Quality analysis

Proximate and physicochemical analyses were conducted on 13-day-old fresh larvae, blanched for 40 s, and on dried larvae at temperatures ranging from 40 °C to 70 °C using the HSED. Dry matter content was determined via the AOAC 950.46 method, involving oven drying at 105 ± 3 °C. Ash content was assessed using the AOAC 942.05 method. Lipids were extracted using the Soxhlet method (AOAC 920.39), and protein content was determined using the Kjeldahl protocol (AOAC 984.13) with a nitrogen-to-protein conversion factor of 4.76. Colour analysis, conducted with a Minolta Chroma meter CR-400, measured L^*, a^*, and b^* values. pH was determined by homogenizing 1 g of BSFL meal in 9 mL of distilled water. All analyses were performed in triplicate.

2.6. Statistical analysis

One-way analysis of variance (ANOVA) was employed to assess variations in mean values for quality analysis. Tukey's post hoc test was then applied to compare the means, with significance set at a P-value below 0.05. These analyses were conducted using IBM SPSS Statistics 25 software.

2.7. Uncertainty analysis

During the drying trials, variations and uncertainties in temperatures, relative humidity, solar radiation, and product mass may arise from factors such as environmental conditions, calibration discrepancies, observations, human error, etc. These were identified using appropriate instruments. Let W_R represent the experimental uncertainty in the outcome, while W_1, W_2, W_3 … W_n denote the experimental uncertainty values in the independent variables. This function is applicable only when the uncertainty in independent variables is provided with the same oddity [27]:

$$W_R = \left[\left(\frac{\partial R}{\partial X_1}W_1\right)^2 + \left(\frac{\partial R}{\partial X_2}W_2\right)^2 + \ldots\left(\frac{\partial R}{\partial X}W_n\right)^2\right]^{1/2} \tag{33}$$

Wherein: R denotes a function relying on independent variables (e.g., humidity, temperature, etc.)

The detailed parameters of the measuring instruments, along with their corresponding uncertainty results, are presented in Table 2.

The calculation of total measurement uncertainty is done as follows:

Temperature:

$$W_T = \left[W^2_{Thermocouples} + W^2_{Thermometer} + W^2_{Connectionpoints} + W^2_{Reading}\right]^{1/2} = \left[(0.3)^2 + (0.3)^2 + (0.6)^2 + (0.5)^2\right]^{1/2} = 1.04^\circ C$$

Relative humidity:

$$W_{RH} = \left[W^2_{Hygrometer} + W^2_{Reading}\right]^{1/2} = \left[(0.6)^2 + (0.5)^2\right]^{1/2} = 0.78\ \%$$

Solar radiation measurement:

$$W_{SR} = \left[W^2_{Pyranometer} + W^2_{Reading}\right]^{1/2} = \left[(8)^2 + (5)^2\right]^{1/2} = 9.43\ W\big/m^2$$

Mass measurement (for drying process):

$$W_{DP} = \left[W^2_{Balance} + W^2_{Reading}\right]^{1/2} = \left[(2)^2 + (0.1)^2\right]^{1/2} = 2.00\ g$$

Mass measurement (for moisture determination):

$$W_{MD} = \left[W^2_{Balance} + W^2_{Reading}\right]^{1/2} = \left[(0.2)^2 + (0.1)^2\right]^{1/2} = 0.22\ g$$

Table 2
Uncertainty of instruments.

Independent variables	Instruments	Model	Range	Total uncertainty
Temperature measurement	Temperature transmitter	Kimo TM-110 pt100	−100 – 400 °C	1.04 °C
Relative humidity measurement	Humidity transmitter	Kimo HM-110	5–95%	0.78 %
Solar radiation measurement	Pyranometer	Kip and Zonen CMP3	0–2000W/m^2	9.43 W/m^2
Mass measurement	Digital balance for drying process	Kern PNJ 12000-1M	0–12 kg	2.00 g
Mass measurement	Digital balance for moisture determination	Kern ABT 220-4 M	0–220 g	0.22 g

3. Results and discussions

3.1. Performance of the solar dryer

The hybrid dryer was tested in an unloaded condition during the autumn season on November 23, 2023. Two drying modes were tested: the exclusively solar drying mode and the hybrid drying mode, which uses both solar energy and electrical energy supplied by a 250W power rating resistor. Data recording was conducted every hour from 9 a.m. to 5 p.m. Fig. 5 depicts the variation in ambient temperature and solar radiation over time. Notably, the peak radiation, reaching 588 W/m^2 at 13:00, coincided with an average ambient temperature of 18.9 °C, attributed to partially cloudy weather during the testing period.

Fig. 6 displays the variation of ambient temperature, drying chamber temperature, and the temperature at the outlet of the collector over time for both the solar and the hybrid modes. The temperature at the solar air heater outlet increases with time and reaches a peak of 60 °C. By adopting the solar mode only, the temperature inside the room reaches a maximum of 55 °C at 2 p.m., even though the maximum ambient temperature is only 22 °C. This demonstrates the effectiveness of the solar mode alone in drying high-moisture products at temperatures below 55 °C under similar weather conditions. The hybrid mode effectively uses both solar and electrical power to achieve a maximum room temperature of 73 °C at 2 p.m. This innovative approach combines these energy sources synergistically, significantly boosting the overall heating capacity in the room. The integration of electrical energy complements the solar input, providing improved control and adaptability to attain and maintain higher temperatures while addressing the interruption in the drying process during the night time.

Fig. 7 illustrates the changes in ambient and drying chamber relative humidity over time for both the solar and hybrid modes. The fluctuation in relative humidity demonstrates an inverse relationship with temperature. The drying chamber relative humidity is observed to be lower than the ambient humidity, a phenomenon attributed to the elevated

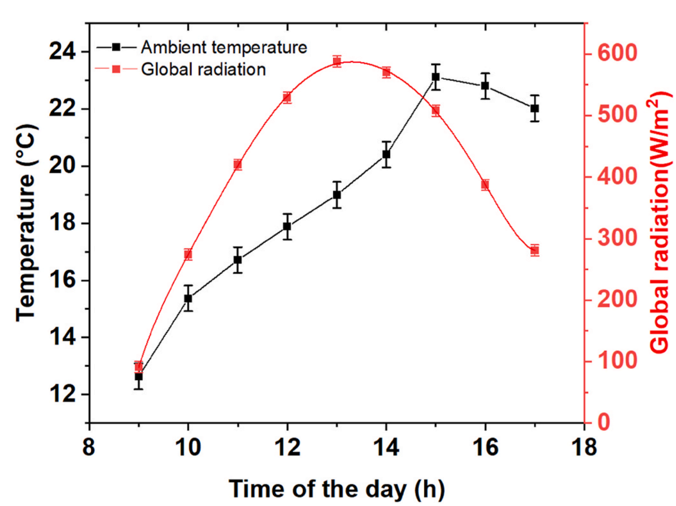

Fig. 5. Evolution of ambient temperature and solar radiation over time.

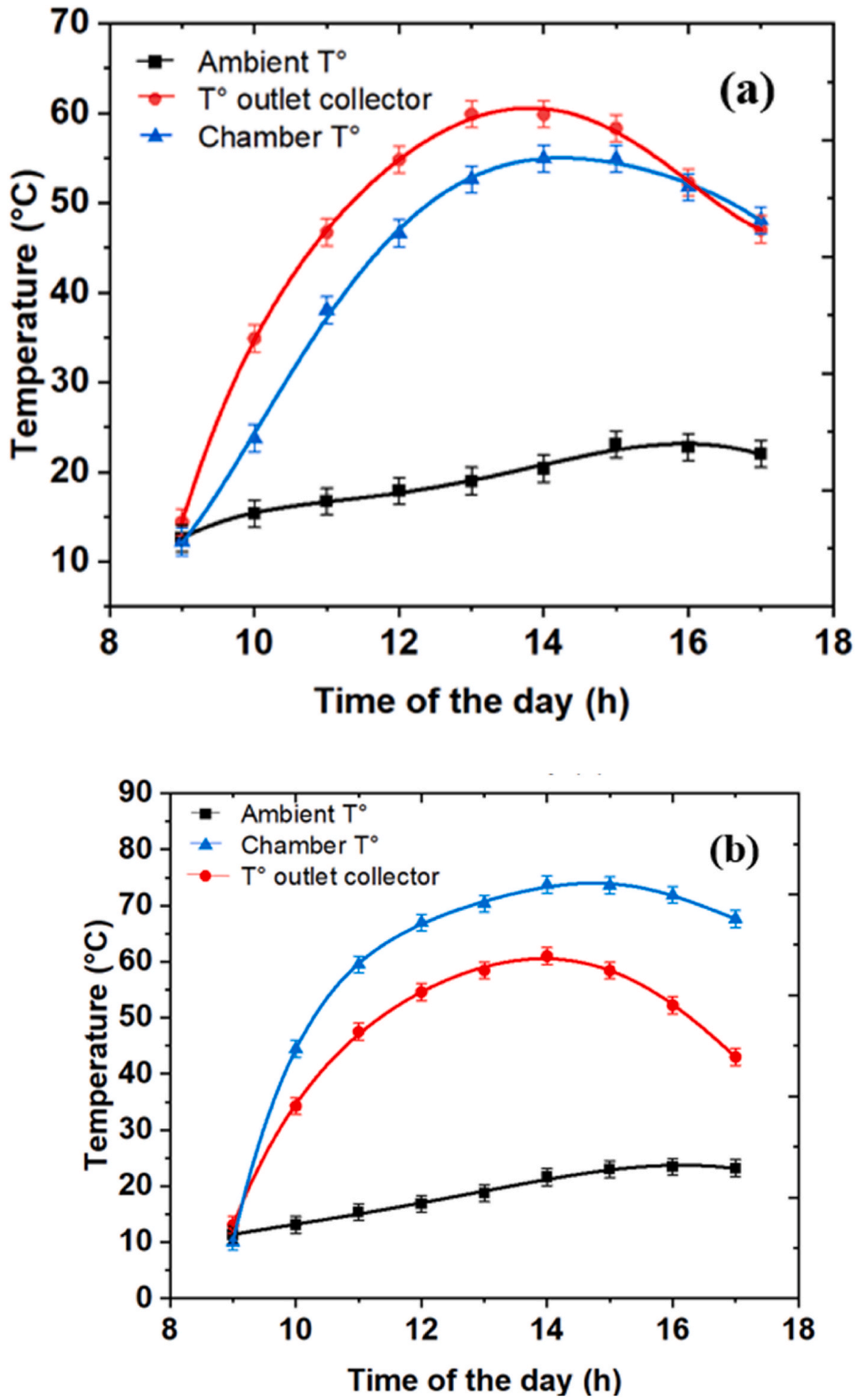

Fig. 6. Variation of ambient temperature, drying chamber temperature, and the temperature at the outlet of the collector over time: (a) solar mode, (b) hybrid mode.

chamber temperature in comparison to the ambient conditions. There was no difference in relative humidity between the two modes studied.

3.2. Drying kinetics

The evolution of moisture content of BSFL over drying time is depicted in Fig. 8. One kilogram of BSFL with an initial moisture content of 1.78 ± 0.07 (kg water/kg dry matter) (63 % wet basis) was subjected to drying at four temperatures (40, 50, 60, and 70 °C) using the HSED. The drying process aimed to achieve a final moisture level within the range of 0.13 to 0.10 (kg water/kg dry matter). The drying times of larvae at 40, 50, 60, and 70 °C were 21, 16, 6, and 2 h, respectively. Drying at 60 °C demonstrates remarkable efficiency, being nearly three times faster compared to the drying process at 50 °C. This significant disparity is attributed to the substantial influence of drying temperature on water evaporation. The relationship between drying time and temperature is non-linear, influenced by thermodynamic factors such as effective moisture diffusivity. The elevated temperature plays a crucial

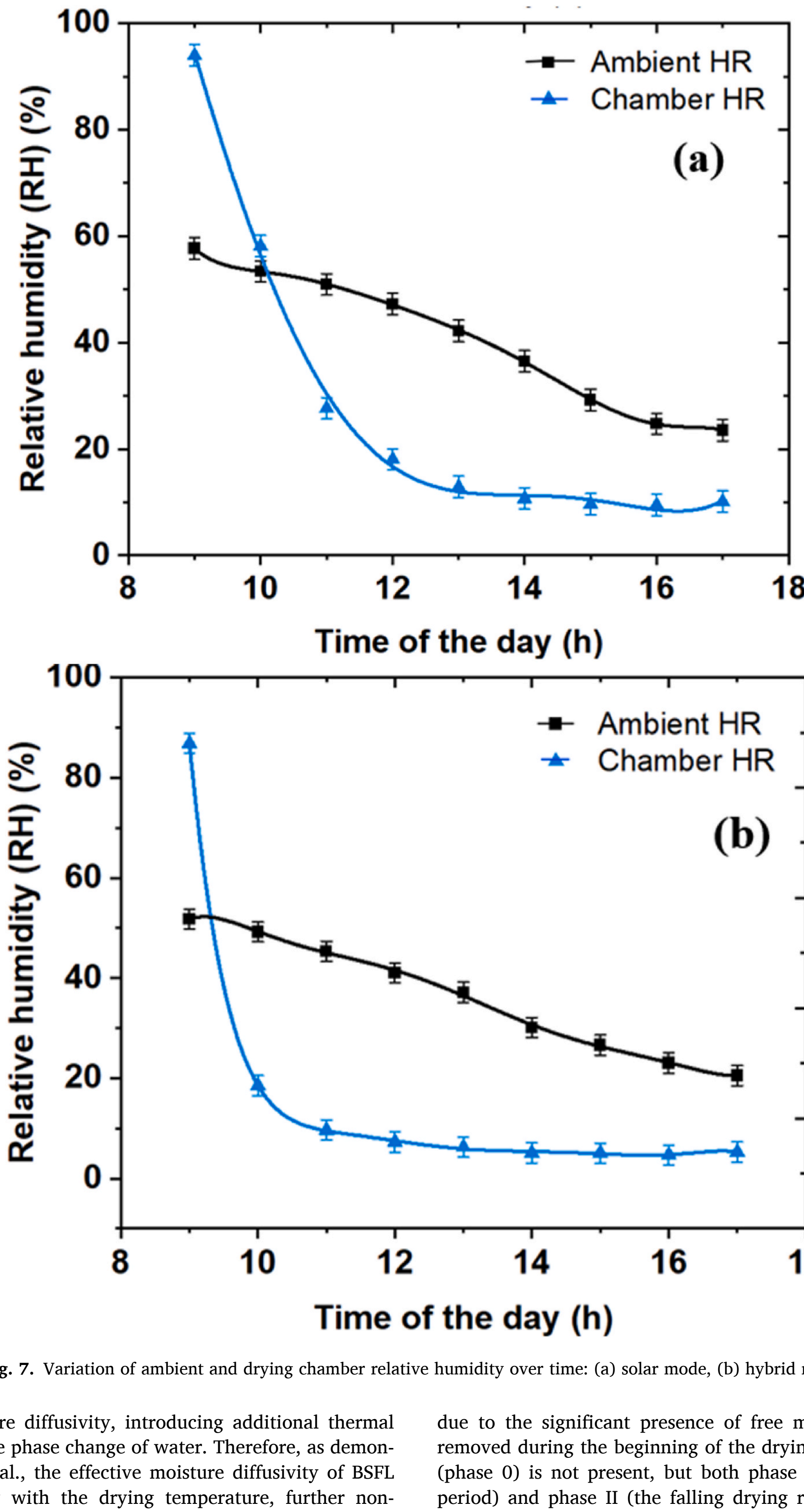

Fig. 7. Variation of ambient and drying chamber relative humidity over time: (a) solar mode, (b) hybrid mode.

role in affecting moisture diffusivity, introducing additional thermal energy that expedites the phase change of water. Therefore, as demonstrated by Peinheiro et al., the effective moisture diffusivity of BSFL increases proportionally with the drying temperature, further non-linearly accelerating the drying process [28]. This trend highlights the pronounced influence of temperature on the efficiency of the drying process, demonstrating a significant reduction in drying time with increasing temperature.

Fig. 9 illustrates the variation in drying rates over time at the four temperatures under consideration. The drying process was initially fast due to the significant presence of free moisture that was promptly removed during the beginning of the drying process. The initial phase (phase 0) is not present, but both phase I (the constant drying rate period) and phase II (the falling drying rate period) are observable. Furthermore, with an increase in temperature, there is a corresponding acceleration in the drying process of BSFL. Notably, the drying time at 70 °C is almost 10 times faster than at 40 °C, and drying at 60 °C is nearly three times faster than at 50 °C. Consequently, drying BSFL below 50 °C proves ineffective, and thus, the performance of the dryer is not utilized. This can be attributed to the impact of high temperature on water

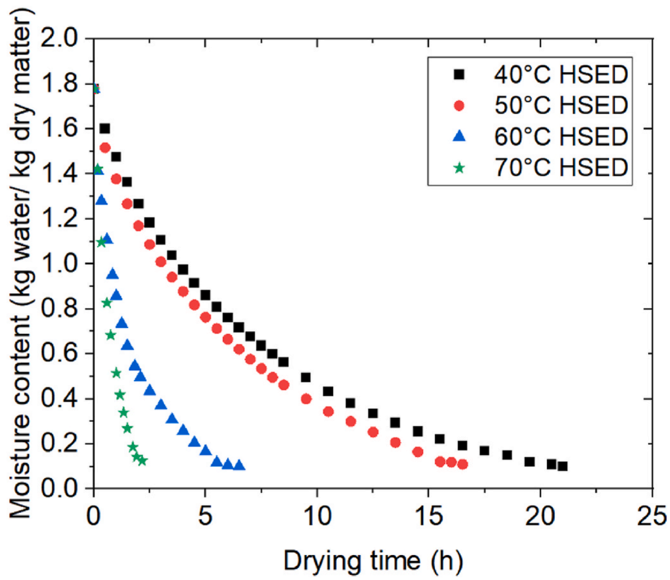

Fig. 8. Evolution of moisture content of black soldier fly larvae over drying time.

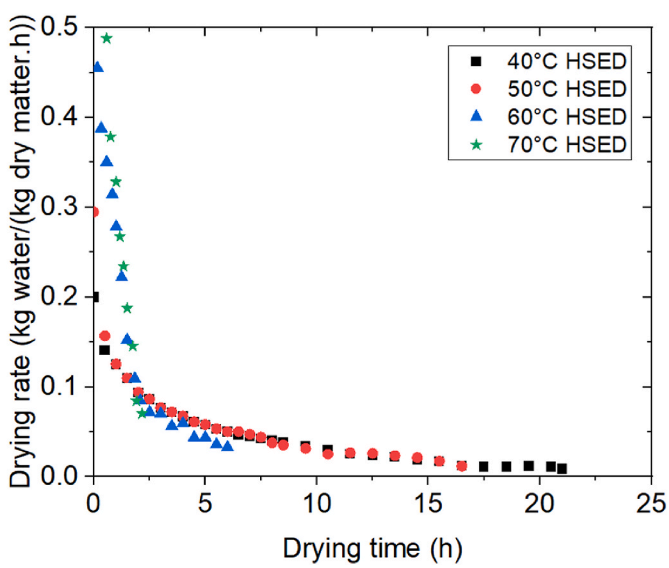

Fig. 9. Evolution of drying rate of black soldier fly larvae over drying time.

diffusivity, providing extra thermal energy that promotes the phase change of water from liquid to vapor, contributing to faster evaporation. Similar trends were observed in the drying behavior of insects from other species, such as yellow mealworm (*Tenebrio molitor*) and house cricket (*Acheta domestica*) [29,30].

3.3. Environmental analysis

The total estimated mass of the current dryer system, comprising various components, is 72.6 kg. Fig. 10 illustrates the mass ratios of the components used. The predominant portion of the mass is attributed to the steel sheet material, accounting for 32.37% or 23.5 kg, followed by aluminium sheet at 27% or 20.3 kg. The remaining mass is distributed among other materials, including the glass cover, iron, plastic, copper, and so forth.

Table 3 lists the embodied energy values of the materials used in the construction of the dryer, along with their respective embodied energy coefficients and Fig. 11 represents the proportion of embodied energy for each component used to fabricate the HSED.

The total embodied energy of the dryer is 1848.596 ± 154.79 kWh. This energy consumption correlates directly with the emission of carbon dioxide, contributing to the release of greenhouse gases. The aluminium sheet accounts for the highest share of embodied energy at 60.7%. This can be attributed both to its mass used in manufacturing, in contrast to materials such as plastic (0.3%), copper (1.1%), and fittings (0.7%), and to its manufacturing process, which demands a comparatively greater amount of energy. This is unlike materials like steel sheet (11.3%), fiberglass insulation (2.3%), and glass cover (2%).

Drying at 60 °C using the HSED involves 89.45% solar energy and 10.54% electrical energy. The significance of solar energy contribution becomes particularly notable in the hybrid system, especially at lower target temperatures (below 60 °C). Furthermore, it is advised not to exceed 60 °C during the drying of BSFL based on experimental findings.

Table 3
The embodied energy of the hybrid solar-electrical dryer.

Material	Quantity (kg)	Embodied energy coefficient (kWh/kg) [26]	Total (kWh)
Aluminium sheet	20.3	55.28	1122.184
Glass cover toughened	5	7.28	36.4
Steel sheet	23.5	8.89	208.915
Iron	14	25	350
Plastic (PVC)	0.3	19.44	5.832
Copper	1	19.61	19.61
Paint	2	25.11	50.22
Fittings (nuts, bolts, screw and rivets)	1.5	8.89	13.335
Fiberglass insulation (glass-wood)	5	8.42	42.1
		E_m Total	**1848.596**

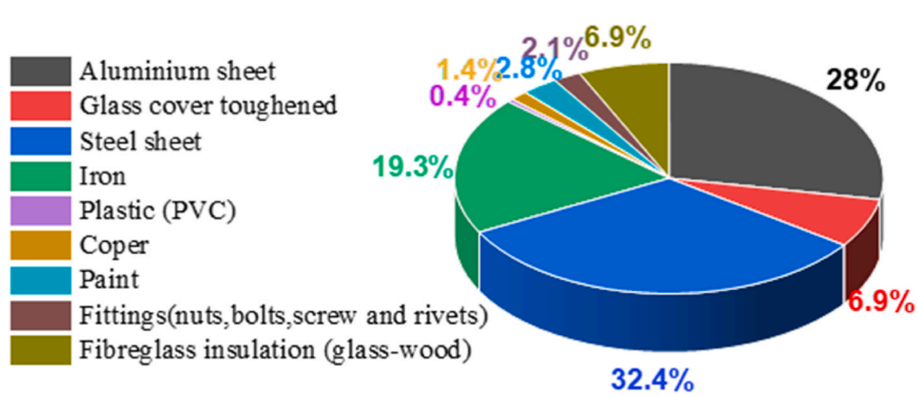

Fig. 10. Pie chart of the masses of materials used for the design of the hybrid solar-electrical dryer.

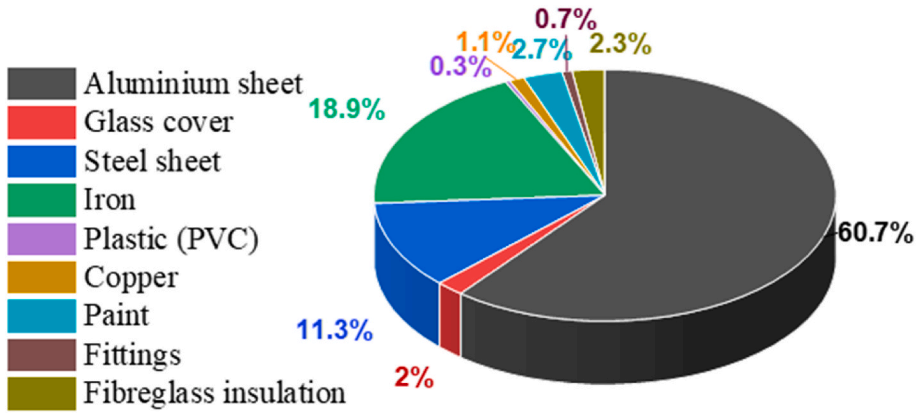

Fig. 11. Pie chart of the embodied energy of materials used for the design of the hybrid solar-electrical dryer.

Beyond this threshold, there is evidence of deterioration in the nutritional and physicochemical quality of the larvae, encompassing proteins, lipids, ash content, and colour, as outlined in Section 3.5.

Table 4 presents a comparison between the environmental parameters of this dryer and those of other solar systems. Compared to other solar dryers, the developed HSED exhibited high environmental efficiency. The energy payback time (EPBT) for this dryer is found to be 1.57 ± 0.09 years which is remarkably low when compared to other existing solar dryers [31–35], and significantly below the expected lifespan of the dryer, which is 25 ± 1.00 years. The dryer produced low CO_2 emissions, totalling 72.58 ± 2.90 kg CO_2/year, much lower than other solar dryer [31–33,36]. A significant net CO_2 mitigation of 57.19 ± 2.35 tons of CO_2 during the dryer's lifetime, coupled with a high annual CO_2 mitigation of 2.36 ± 0.33 tons/year were recorded compared to other hybrid dryers [31,32,34,35], and the carbon credits earned ranged from 285.97 to 1143.88 USD. Therefore, employing the HSED with a solar energy utilization rate of 89.45% and 10.55% reliance on electrical energy during drying at 60 °C succeeded in minimizing the annual CO_2 emissions and consequently enhancing CO_2 mitigation. As the solar energy utilization rate increases in the hybrid dryer, both the reduction in CO_2 emissions and the enhancement of CO_2 mitigation also increase [37].

3.4. Economic analysis

The economic analysis is a crucial determinant in affirming the

Table 5
Economic and cost variables associated with using the hybrid solar-electrical dryer for drying black soldier fly larvae.

Variable	Cost
C_{ccd}: Capital cost of the dryer (USD)	1029.74
C_{acc}: Annualized capital cost (USD)	220.17
C_{mc}: Annualized maintenance cost (USD)	22.02
S: Salvage value (USD)	102.97
S_a: Annualized salvage (USD)	3.21
C_{rec}: Annualized running electricity cost (USD)	784.99
AC: Annualized cost (USD)	1023.96
CD_{kg}: Cost of dried product per kg (USD/kg)	1.07
C_{fre}: Cost of fresh product per kg (USD/kg)	3
C_{dry}: cost of fresh product intended for solar drying per kg of dried product (USD/kg)	9.37
C_{drys}: Cost per kg of dried product (USD/kg)	10.44
C_{bdp}: Selling price of branded dried product (USD/kg)	12
B_{kg}: Savings per kg of the obtained dried product (USD/kg)	1.56
B_d: Savings per drying day (USD)	4.99
B_j: Annual saving (USD)	1496.04
i: Interest rate in Morocco (%)	2
r: Inflation rate in Morocco (%)	8
n: Lifetime of the dryer	25
P_b: Payback period (year)	0.72

Table 4
Environmental parameters of the hybrid solar-electrical dryer as compared with other solar dryers documented in the literature.

Type of the dryer	E_m (kWh)	EPBT (year)	CO_2 emission (kg/year)	Net CO_2 mitigation (ton/lifetime)	ECC (USD)		Reference
					min	max	
Hybrid solar-electrical dryer	11848.596	1.57	72.58	57.19	285.97	1143.88	Present study
Solar dryer-assisted solar water collector	1531.479	8.66	100.05	25.18	133.5	534	[31]
Indirect solar dryer with offset strip fins	1338.46	2.03	87.45	17.458	87.29	349.16	[32]
Indirect solar dryer	1081.8	4.36	85.46	391.52	575.68	2302.74	[33]
Indirect solar dryer unit	1109.3	2.21	31.06	33.52	133.41	533.63	[34]
North wall insulated greenhouse dryer under forced convection mode	750.4	2.35	21.01	36.34	149.06	596.27	[35]
Hybrid photovoltaic-thermal (PVT) mixed-mode greenhouse solar dryer	2082.2	1.23	170.08	81.75	817.50	__	[36]

feasibility of the recently developed solar dryer. This thorough examination not only highlights the economic viability of the system but also offers essential insights into its financial sustainability and potential for long-term benefits. Table 5 illustrates the diverse economic parameters calculated to assess the economic feasibility of the HSED. The capital cost of the dryer was 1029.74 USD. The annual maintenance cost was considered 10% of the annualized capital cost, resulting in an annualized cost of 1008.55 USD. The salvage value, representing the estimated resale value of the dryer after its economic life, was calculated at 10% of the capital cost. Given the consistent solar radiation in Morocco, where the experiments were conducted, the number of drying days was estimated at 300 per year. The annual amount of dried product was found to be 960 kg/year.

The payback period was estimated at 8 months, which is extremely short when compared to the dryer's lifetime. This payback period value was compared to that of other hybrid solar systems, as illustrated in Table 6. The dryer's remarkably short payback period can be attributed to several key factors in the context of Morocco. Firstly, the construction of the dryer benefits from the low cost of raw materials in the country. Additionally, the favorable economic environment is further supported by low-interest rates provided by Moroccan banks, standing at 2%. The availability of banking facilities enhances financial accessibility. Furthermore, the economics of the BSFL contribute significantly, with the fresh larvae being cost-effective at 3 USD, while their value increases substantially to 12 USD in the dried form.

The HSED offers the potential to save up to 1.56 USD per kilogram of the obtained dried product. When utilized for drying BSFL, it can result in daily savings of up to 4.99 USD and yearly savings of 1496.04 USD. This amount holds considerable significance in an emerging and middle-income country like Morocco, especially considering that the average daily per capita salary was approximately 8 USD in 2021 [44]. The dryer's cumulative savings over its 25-year lifespan could amount to 9486.65 USD, as illustrated in Fig. 12. This suggests its appropriateness, given the substantial and consistent annual as well as total savings it offers.

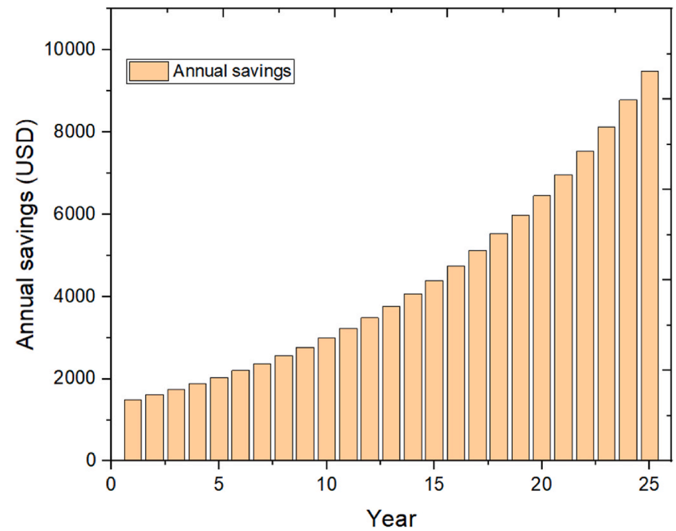

Fig. 12. Annual savings of the hybrid solar-electrical dryer.

3.5. Quality analysis

The nutritional and physicochemical composition of fresh larvae blanched at 100 °C for 40 s, as well as larvae blanched and subsequently dried using the HSED at temperatures of 40 °C, 50 °C, 60 °C, and 70 °C, is detailed in Table 7.

The moisture content of BSFL experienced a significant reduction through the drying process. Initially, fresh blanched larvae exhibited a moisture content of 1.78% (kg water/kg dry matter), while dried larvae demonstrated a maximum moisture content of 0.13 (kg water/kg dry matter). These findings underscore the efficacy of drying as a valuable technique for extending the shelf life of BSFL. Furthermore, the low moisture levels suggest that dried BSFL can be stored at room temperature.

Table 6
Comparison of the current payback period value with recent hybrid solar dryer.

Type of the dryer	Payback period (year)	Reference
Hybrid solar-electric dryer	0.71	Current study
Solar dryer-assisted solar water collector	4.95	[31]
hybrid active greenhouse solar dryer	1.73	[38]
Hybrid solar-electric dryer	0.72	[39]
Solar dryer with and without geothermal water heat exchanger	2.21/8.44	[40]
Solar-assisted heat pump fluidized bed dryer integrated with a biomass oven	1.6	[41]
Solar dryer equipped with a biomass heater	3.3	[42]
Greenhouse cabinet integrated mixed mode solar dryer with and without phase change material	0.80/0.87	[43]

The larvae dried by this HSED exhibited a protein content within the range of 42.33%–38.14%, making it highly competitive in the market. This protein range not only satisfies but also surpasses the minimum requirement of 34% observed in larvae produced by leading companies in the insect production market [45,46]. This quality assurance positions BSFL dried by this hybrid system as an excellent choice for industrial companies, meeting their stringent standards and preferences for protein-rich larvae.

Furthermore, the larval crude protein and lipid contents obtained in this study were found to be higher than those reported in previous studies for BSFL, whereas the ash content was similar [21,22,47]. This may result from the age of the larvae at harvest, the type of rearing substrate used, the killing method employed, and especially the drying technique utilized [48]. Drying significantly impacted the levels of crude protein and crude fat in BSFL ($P < 0.05$), leading to a decrease compared to fresh larvae. Additionally, higher drying temperatures were associated with an increased rate of protein and lipid loss. This can be attributed to protein denaturation and browning reactions, utilizing amino acids and resulting in a reduction in protein content. Simultaneously, higher drying temperatures accelerate fat oxidation, resulting in a reduction of fat content [9]. After drying, there was a significant ($P < 0.05$) increase in ash content, attributed to elevated mineral levels [49].

The nutrient loss, particularly in proteins and lipids, between larvae dried at 50 °C (with protein content at 41.07% and lipid content at 24.76%) and those dried at 60 °C (with protein content at 39.08% and lipid content at 23.50%), is minimal. The marginal decrease in nutrient values suggests that drying at 60 °C is the preferred drying temperature since it enables a threefold reduction in drying time while maintaining an interesting nutritional profile. Moreover, when assessing the quality of larvae subjected to drying at 60 °C, the hybrid dryer outperforms conventional drying methods at the same temperature [22,50]. The protein content of larvae dried with the hybrid method surpasses that of conventionally dried larvae by a significant margin of 7.08% [22].

The pH of the larvae was notably high (pH ranging from 8.46 to 9.25), exceeding the recommended value (pH = 4.6) [23]. This elevation is linked to the blanching process used as a killing technique, resulting in the leaching of ascorbic acid and a subsequent rise in pH [51]. Nevertheless, this alkaline pH level can be advantageous, inhibiting microbial growth, as observed in the case of egg white [52].

As expected, drying at a low temperature (T° = 40 °C) did not significantly affect the color of dried larvae compared to fresh larvae, as

Table 7
Nutritional and physicochemical composition of fresh and dried larvae using the hybrid solar-electrical dryer (n = 3; mean ± standard error).

Parameters	Fresh	Dried at 40 °C	Dried at 50 °C	Dried at 60 °C	Dried at 70 °C
Water content (kg water/kg dry matter)	$1.70^{a}\pm0.07$	$0.13^{b}\pm0.11$	$0.12^{b}\pm0.19$	$0.12^{b}\pm0.22$	$0.10^{b}\pm0.23$
Protein (g/100g)	$45.70^{a}\pm0.60$	$42.33^{b}\pm0.12$	$41.07^{bc}\pm0.53$	$39.08^{d}\pm0.26$	$38.14^{e}\pm0.28$
Lipid (g/100g)	$32.60^{a}\pm0.31$	$29.37^{b}\pm0.39$	$24.76^{c}\pm0.32$	$23.50^{cd}\pm1.07$	$21.24^{e}\pm0.88$
Ash (g/100g)	$7.13^{b}\pm0.02$	$7.98^{a}\pm0.01$	$7.60^{a}\pm0.07$	$7.49^{a}\pm0.06$	$7.35^{a}\pm0.02$
pH	$8.46^{d}\pm0.01$	$8.89^{c}\pm0.12$	$9.08^{b}\pm0.03$	$9.22^{b}\pm0.06$	$9.25^{a}\pm0.01$
L^*	$51.23^{a}\pm0.39$	$50.46^{a}\pm0.34$	$47.91^{b}\pm0.52$	$44.34^{c}\pm0.89$	$40.80^{d}\pm0.76$
a^*	$7.13^{a}\pm0.11$	$6.92^{b}\pm0.55$	$5.81^{c}\pm0.04$	$5.69^{cd}\pm0.07$	$5.68^{d}\pm0.08$
b^*	$25.91^{a}\pm0.12$	$24.29^{a}\pm0.09$	$23.75^{a}\pm0.04$	$23.71^{ab}\pm0.15$	$24.11^{b}\pm0.05$
ΔE	Reference	$1.98^{d}\pm0.46$	$4.19^{c}\pm0.34$	$7.37^{b}\pm1.26$	$10.68^{a}\pm1.20$

Distinct letters in the same row indicate significant differences (ANOVA 1, $P < 0.05$).

indicated by a ΔE of less than 2 ($\Delta E = 1.98$) [23]. However, as the temperature of the drying air increases, the color change becomes more noticeable, accompanied by a reduction in lightness (L^*). The observed color alteration between fresh larvae and dried larvae can be attributed to various factors. Enzymatic browning reactions play a role, involving the oxidation of polyphenols and the subsequent formation of complex between iron and polyphenols [53,54]. Additionally, non-enzymatic browning reactions occur between amino acids and reducing sugars, contributing to the overall change in color [55]. Furthermore, when examining the difference in color among dried larvae at various temperatures, the intensification of the darkening effect with increasing temperature becomes apparent. This heightened effect can be explained by the influence of temperature on both enzymatic and non-enzymatic browning reactions. As the drying temperature rises, the activity of enzymes and the rate of non-enzymatic reactions accelerate, leading to a more pronounced alteration in color and an intensified browning effect on the larvae [56].

4. Conclusion and perspectives

The drying kinetics of BSFL were experimentally studied at 40, 50, 60, and 70 °C using a hybrid solar-electrical dryer (HSED). Additionally, the environmental and economic analysis of the dryer, as well as the quality analysis of the dried BSFL, were investigated. The main findings are highlighted below.

- The solar mode alone has proven effective in drying high-moisture product, particularly at temperatures below 55 °C in cold ambient weather conditions. Electrical resistance can complement the drying process by ensuring continuous overnight drying and aiding in the control and maintenance of drying conditions.
- Temperature significantly affects BSFL drying kinetics, particularly at temperatures exceeding 60 °C. Transitioning from 60 °C to 50 °C results in a 62.5% reduction in drying time, and lowering the temperature from 60 °C to 40 °C leads to a further 71.43% reduction.
- The energy payback time of the HSED is found to be 1.57 ± 0.09 years.
- Utilizing local materials to construct the developed dryer reduces CO_2 emissions in the environment to 72.58 ± 2.90 kg CO_2/year and effectively mitigates 57.19 ± 2.35 tons of CO_2 over its lifespan. The range of earned carbon credits falls between 285.97 and 1143.88 USD. Therefore, the HSED is recognized for its environmental friendliness, emitting minimal greenhouse gases into the atmosphere.
- The economic study showed interesting results: the HSED demonstrates a short payback period of only 0.71 years in contrast to its 25-year lifespan. Furthermore, the dryer has the potential to annually save up to 1496.04 USD, marking a significant economic and financial benefit.
- The nutritional composition of BSFL undergoing drying through this system exhibits noteworthy characteristics; particularly a high protein content compared to conventional drying methods and dried larvae produced by international market leaders.
- Increasing the drying temperature significantly decreases the nutritional quality of the larvae compared to fresh blanched larvae. However, drying at 60 °C appears to be the optimal temperature for drying BSFL, demonstrating both interesting nutritional quality and minimal drying time.

Based on the aforementioned results, employing the HSED is highly recommended for drying BSFL in Morocco. These findings not only advocate for the widespread adoption of such dryers for large-scale production in the region but also underscore the significance of investing in solar energy. The HSED proves to be not only economically sustainable but also environmentally friendly, thereby reinforcing its viability and potential positive impact in the Moroccan context. Efforts are still required to ensure the seamless integration of this hybrid dryer into a continuous production unit. In prospect, this study envisions further enhancing the sustainability of the HSED by exploring the feasibility of harnessing electrical energy from various renewable sources. Beyond solar energy, the integration of wind turbines or biomass is envisaged as a strategically advantageous endeavor. This forward-looking step not only aligns with prevailing global green energy trends but also enhances the economic and environmental merits of the HSED.

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CRediT authorship contribution statement

Manal Lehmad: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nawfal Hidra:** Software, Formal analysis, Data curation. **Patrick Lhomme:** Writing – review & editing, Investigation. **Safa Mghazli:** Writing – review & editing. **Youssef EL Hachimi:** Writing – review & editing, Supervision. **Naji Abdenouri:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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