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Development of a Solar-Powered Barley Sprouting Room

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ABSTRACT

The study aims to develop a sprouting room for barley powered by solar energy instead of traditional alternating-current rooms to suit remote areas. The cooling, lighting, and irrigation systems were developed and replaced with another that operates on 12 V DC. An air-cooling device based on the Peltier module has been developed as an alternative to air conditioning devices. Four cooling units of the air cooler were tested with three lighting durations of 6, 9, and 12 h and three irrigation rates of 1.7, 1.85, and 2 m^3 ton^{-1}. The measurements included evaluating the performance of the developed air cooler device. The vegetative and quality characteristics and a chemical analysis of sprouted barley for the solar-powered room compared to the room before the modification was estimated. The solar room's productivity and electrical energy consumption rates were calculated, and an economic evaluation of the development was conducted. The maximum electrical power consumption for the solar-powered sprouting room was 63.275 kWh ton^{-1}, compared with 117.19 kWh ton^{-1} for the alternating current-managed room before modification. The interaction between the DC air cooling, lighting and irrigation used achieved standard rates for the vegetative and quality characteristics of the barley produced. The maximal productivity from sprouted barley was 1.22 tons per 7 days with an increment ratio over control of 31.97%. The net earnings for the developed sprouting room were maximized relative to the significant decrease in electrical production costs. The developed sprouting room fits the livestock sector by providing good economical alternative fodder sources.

Keywords: *Arduino, Controller, Cooler, Panel, Remote, Strips*

INTRODUCTION

Addressing the rising demand for food and livestock feed, particularly in urban areas, is crucial, with the global population expected to reach 10 billion by 2050 (Ghorbel *et al.*, 2021). This increase will also drive higher demands for energy and water resources which are inevitably interrelated (Degirmencioglu *et al.*, 2019). Hydroponic systems offer efficient, high-moisture forage production methods, especially valuable in arid desert regions facing fodder scarcity like Egypt (Mariyappillai *et al.*, 2020). Barley sprouting via hydroponic systems ensures a steady supply of green fodder, conserving water, reducing labor, and minimizing reliance on chemical inputs. This paper explores managing barley sprouting rooms with solar-powered solutions, offering a sustainable approach to meet modern agriculture's evolving demands.

The benefits of barley sprouts for year-round green fodder production underscore their significance in sustainable agriculture. Compared to conventional methods, barley sprouting requires approximately 80% less water and typically lasts only 7-8 days (Farghaly *et al.*, 2019). Additionally, 50 m^2 of sprouting rooms yield the same productivity as 2.94 hectares of alfalfa cultivation annually (Hegab, 2018). Barley sprouts provide nutrient-rich forage options, particularly beneficial for ruminants such as cattle, sheep, and goats due to their protein, vitamin, and enzyme content (Helal, 2015). Protein-rich fodder can strain breeders financially. Additionally, the pesticide-free nature of sprouted fodder enhances animal immunity, reduces disease risk, and helps alleviate thirst, especially in the summer (Basko, 2009). Unlike concentrated feed, Barley sprouts' natural yeasts aid in cellulose digestion without causing bloating or acidity in animals, leading to improved animal specifications, fertility, and reproduction rates (Izydorczyk and Edney, 2017).

However, constructing sprouting rooms poses financial challenges for small-scale breeders, necessitating innovative cost-reducing solutions while maintaining production quality. These rooms rely on hydroponic systems, requiring artificial factors such as lighting, irrigation, and temperature control, which can escalate production costs due to electricity consumption and fuel expenses for generators in areas without electricity (Basko, 2009). Hydroponic systems are essential in barley sprouting rooms, yielding ample plant material quickly. Kumari *et al.* (2018) also discovered that incorporating fresh barley sprouts into livestock diets can enhance health, reduce heat stress, and improve birth rates. Technological advancements in sprouting methods have enhanced economic competitiveness, which is crucial in regions with limited forage production (Adegbeye *et al.*, 2020).

Precise water and nutrient level control is crucial to managing increasing costs and securing expected profits. Dung *et al.* (2010) maintained a consistent temperature of 25°C and continuous lighting over a 7-day barley sprouting period using a hydroponic unit in a temperature-controlled environment, employing fluorescent lamps with an average light intensity of about 615 lux. The results showed fresh sprouts weighed about 3.7 times their pre-steeped weight after seven days. For optimal synthesis and release of plant bioactive compounds, longer sprouting durations (3 to 5 days) and higher processing temperatures (25 to 35°C) are usually necessary. Nutritional changes during sprouting offer various health benefits (Lemmens *et al.*, 2019). Proteins convert into essential amino acids, carbohydrates into sugars, and fats into essential fatty acids. This enzymatic activity increases, enhancing digestibility compared to dry seeds (Shit, 2019). Producing hydroponic green forage through sprouting takes 8-15 days and minimal land (Bazeley and Hayton, 2013; Gebremedhin, 2015). From one kilogram of seeds, approximately 6 to 10 kilograms of fresh green sprouts can be generated annually (Soufan *et al.*, 2023). These sprouts, consisting of germinated seeds with intertwined roots and green shoots, are consumed entirely by livestock. Barley seeds, being affordable and widely available, are preferred. They maintain a crude protein content of 16-17% with over 85% in vitro digestibility, and high levels of vitamin E and beta-carotene, promoting animal fertility (Atlas, 2004). Hydroponic fodder production drastically reduces water usage. For instance, it requires about 3 liters of water per kilogram of fresh hydroponic feed, compared to 73 liters under conventional field conditions (Sharma *et al.*, 2018; Ramteke *et al.*, 2019).

Hydroponic techniques are recognized as a successful alternative for sustainable livestock farming (Ramteke *et al.*, 2019). The chemical composition of hydroponically germinated barley fodder is influenced by the harvesting duration, with the seventh day identified as optimal (Akbag *et al.*, 2014). Chlorophyll indicates nitrogen levels in plants, which is crucial for plant health (Marsh, 2016). Sprouting under net houses yields superior physical characteristics and chemical analysis. However, high construction costs for sprouting rooms hinder widespread adoption, particularly in Egypt. The high expenses for temperature control, lighting, and irrigation, which are reliant on electrical power, significantly raise production costs. The high electricity consumption of sprouting rooms increases production expenses and burdens owners (Alrajhi and Elsayed, 2023). Power outages also lead to substantial losses from sprouted barley spoilage. In the remote areas sprouting rooms, owners must buy electric generators, which are considered additional costs due to their cost, fuel prices, and environmental pollution from combustion exhausts. The use of solar energy to manage sprouting rooms is considered a new matter that can be relied upon to save electrical energy consumption and achieve sustainable agricultural development.

Therefore, the research aims to manage barley sprouting rooms with solar energy to operate alternative DC-developed cooling, lighting, and irrigation systems using solar-powered energy stored in rechargeable batteries to fit remote areas lacking electricity sources. The objectives include: 1) Developing a DC air cooler device and electronic circuit for the automatic control of the cooling, lighting, and irrigation systems in the sprouting room. 2) Studying the engineering production factors influencing the efficiency of the developed sprouting rooms. 3) Conducting an economic analysis of the developed system compared to the pre-developed sprouting room.

MATERIALS and METHODS

Experimental procedure

Experiments were conducted in the barley solar-powered sprouting room on the barley (*Hordeum vulgare* L.) variety Giza 133 from November 2023 to March 2024. The experiments were conducted on a private farm in the Qalabsho city of Dakahlia Governorate, with coordinates 31° 43′ 08″ and 31° 32′ 55″. This desert area was chosen to conduct experiments on the solar-powered barley sprouting room. The average hours of daily solar radiation during the experimental period ranged from 9.2 to 10 hours per day at an average temperature of 25°C and a relative humidity of 75%. The experiments were conducted in a completely randomized block design using five experimental replicates. A barley grain amounting to 625 kg was used to produce 5 tons of sprouted barley. A primary experiment was done to test the developed DC air cooler device separately under the effect of using four levels for cooling units (C1, C2, C3, and C4) with four settled air temperatures (T1, T2, T3, and T4) of 20, 21, 22, and 23°C. The developed solar-powered sprouting room experiments included testing four cooling unit levels for the developed air cooler (C1, C2, C3, and C4). Three durations of the developed LED lighting system were tested (L1, L2, and L3) at 6, 9, and 12 h per day. Three different irrigation rates of the developed irrigation system (I1, I2, and I3) of 1.7, 1.85, and m^3 ton^{-1} were tested.

General description

The solar-powered sprouting room

A solar-powered barley sprouting room has been developed. All electrical systems operate with 12 volt direct current, as shown in Figure 1. The developed room is suitable for sprouting barley in remote areas without a local electricity network. Dual solar panels (12V-100W), a charging circuit, and dual electrical DC batteries (12V-120A) were installed to operate the developed sprouting room, as shown in Figure 1. A closed room was used for sprouting barley with geometric dimensions of 6 m long, 2.75 m wide, and 2 m high, which produces 1 ton of sprouted barley weekly. All AC 220 volts, 50-60 Hz air conditioners, irrigation pumps, and lighting systems were replaced. A developed air cooling device that operates on 12V DC was utilized (Figure 1, No. 2). Fluorescent white LED strips run with 12V DC (24W per reel length of 5 m) were also installed for lighting the solar bowered sprouting room, as shown in Figure 1, No. 7. The LED strip width was 12 mm. The LED type was SMD 5050, with a brightness of 670 lm m^{-1}. The used LED strip type has a life span of 50000 h, a LED density of 60 LEDs m^{-1}, and ambient working temperatures of -20 to +45 °C. Brushless DC water pumps model 1238-B operate on a direct current of 12 V, as shown in Figure 1, No. 5. The used pump body size is 37.5*35*25.5mm (length*width*height), with a net weight of 66 g. The water pump has a maximum flow rate of 240 L h^{-1}, a maximum power consumption of 3.6 W (0.35 A), a maximum height lift of 3 m, and a lifespan of 30,000 hours. A sprinkler irrigation network hose equipped with equally distributed sprinklers was fixed over the sprouting trays, as shown in Figure 1, No. 6.

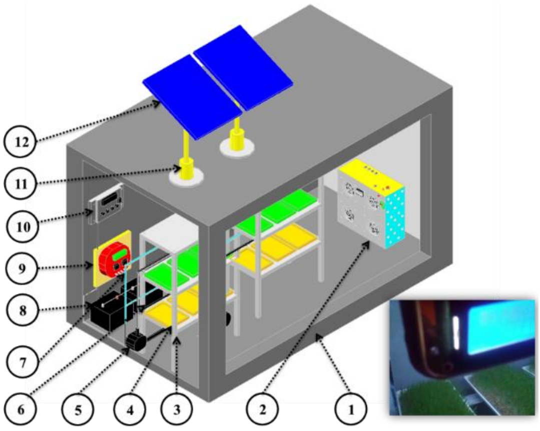

Figure 1. *Isometric view of the solar-powered sprouting room.*
(1-sprouting room; 2-developed DC air cooler device; 3-barley rack holder; 4-barley racks; 5-DC water pump; 6-water nozzles hose; 7- LED strip lights; 8- DC 12V & 120A batteries; 9-arduino controller; 10-solar charger controller; 11- solar guidance motor; 12- 12V &100 W solar panel).

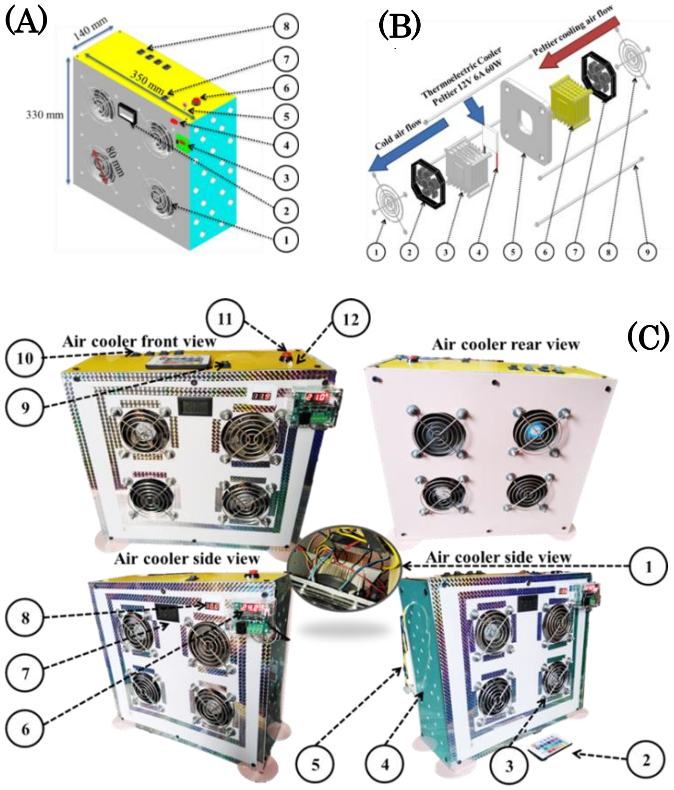

Figure 2. *The developed DC air cooler device.*
(A) Air cooler isometric view: (1- air cooling unit; 2- digital thermostat; 3- temperature controller W1209; 4- volt indicator; 5- infrared receiving lens; 6- temperature controller press switch; 7- main on/off switch; 8- cooler unit switches); **(B)** the cooler forming unit: (1-shield mesh; 2-cold air exit fan; 3-aluminum heat sink; 4-peltier module; 5-fiberboard peltier holder; 6-copper heat sink; 7-peltier cooling fan; 8-shield mesh; 9-screw) and **(C)** air cooler views: (1-inlet cooler unit; 2-remote control; 3-shield mesh; 4-air vents; 5-power supply cable; 6-temperature controller W1209; 7-digital thermostat; 8-volt indicator; 9-main on/off switch; 10-cooler unit switches; 11-temperature controller press switch; 12-infrared receiving lens).

Solar power supply components

Two 100 W solar panels with an open and maximum circuit voltage of 21.6 and 17.3 V were used to supply the sprouting room with electrical energy. The solar panels were fixed on the top room surface, as shown in Figure 1. The short circuit and working current for the solar panels were 6.17 and 5.78 A, respectively, with an output tolerance of ±3%. The working temperature range for the solar panels was -40 to +80°C. The solar panels were connected in parallel, as shown in Figure 1, No. 12. Every solar panel was mounted by a rotating hollow shaft holder that followed the sun's rays using a solar guidance motor, as shown in Figure 1 No. 11. A solar charger controller (Figure 1, No. 10) with a capacity of 20 A and an overcharge protection range of 14.4 to 28.8 V was used to save the generated electrical energy to dual DC batteries (12V and 120A), as shown in Figure 1, No. 8. The solar charger controller and the DC batteries were fixed inside the sprouting room, as shown in Figure 1. The two dual solar panels (200W) generated 16.67A, which was enough to operate the sprouting rooms' DC electrical systems for lighting, cooling, and irrigating.

The developed DC air cooler device

The air cooler device cools the barley sprouting room instead of using an air conditioner. As shown in Figure 2A, the geometric dimensions of the developed air cooler device are 350 mm wide, 330 mm long, and 140 mm thick. The air cooling device weighs 5200 g. The air-cooling device consumed power of 0.255 kW and 12 V DC at entire unit operation. The air cooler device is in the shape of a rectangular box and is easy to move inside the sprouting room according to the position of the sprouted barley tray holder. The outer frame of the air-cooling device is made of 5 mm-thick compressed fiber and is lined with aluminum panels on both sides to resist moisture and heat.

Figure 2C No. 4, shows that the air cooler device is equipped with side ventilation holes to prevent the internal components from heating up. The cooler device contains four separate air cooling units to distribute cold air, each of which can be operated separately. Every air cooling unit consumed 0.06 kW and 12 VDC. As in Figure 2C No. 10, there are four buttons to operate the cooling units. Each air cooling unit, as shown in Figure 2B, consists of a pair of fans, a pair of cooling heat sinks, a peltier, two shield meshes, and four screws. Each 12V, 6A, 60W (40×40 mm) peltier module unit (Figure 2B No. 4) is installed inside a square perforated fiberboard holder 120 mm long and 5 mm thick (Figure 2B No. 5). The hot side of the peltier is installed opposite the copper heat sink (Figure 2B No. 6) because the heat transfer coefficient of copper is higher.

Therefore, the hot side of the peltier is cooled efficiently. The peltier cooling fan is installed opposite the copper heat sink. It draws air internally into the copper heat sink to cool the peltier so that its temperature does not exceed 38ºC (Figure 2B No. 7). The aluminum heat sink and cold air cooling fan are installed from the cold side of the peltier, as shown in Figure 2B, No. 2 and 3. Circular holes with a diameter of 80 mm were made to install the cooling units in the air cooling device, as shown in Figure 2A. The used fans have a diameter of 120 mm and a 25 mm depth, a rotation speed of 2000 RPM, an operating voltage of 12V (0.3A; 3.6W), and an airflow of 65.41 $m^3 h^{-1}$ with a noise level of 36 dBA. Each cooling unit was installed using four 7-mm screws with a length of 140 mm axially, as shown in Figure 2B No. 9. A pair of shield meshes were used on the cooling units, front and back, as in Figure 2B No. 1 and 8.

The operation of the air cooling device is controlled using the remote control (Figure 2C No. 2). An infrared receiving circuit was installed to operate the device, as shown in Figure 2C No. 12. The infrared receiving lens was installed on top of the air cooling device, as shown in Figure 2A No. 5. A voltage indicator (Figure 2C No. 8) has been installed to show the electrical voltage consumed during operation. A thermal controller, model W1209, was used to control the cooling temperatures of the device, as shown in Figure 2C No. 6. The probe for the thermal controller was installed internally and connected to the aluminum heat sink for cooling. The temperature controller W1209 has measurement control accuracy with 0.1 runs at 12 V (0.42 W) and is supplied with a one-channel relay module with a capacity of 10 A. Room cooling temperatures can be controlled from 21 to 23 ºC by programming the temperature controller using its buttons. There is a separate red button (Figure 2A No. 6) to operate the thermal controller. A main button to turn off and turn on the cooling device was used, as shown in Figure 2A No. 7. A digital air thermostat was installed to indicate the room temperatures, as shown in Figure 2C No. 7.

Arduino controller

The operating timing of the irrigation pumps and LED light strips was controlled using an electronic control board with an Arduino, as shown in Figure 3. The Arduino controller consumes electrical power of 1.5 W. The Arduino controller circuit contains a pair of 12V, 125A relays to connect and disconnect the continuous electrical current for the irrigation and lighting systems. The Arduino Nano microcontroller circuit is programmed to control operating time ranges to minimize human intervention. The electronic controller has a digital screen that shows the room's operating programs that can be changed as needed, as shown in Figure 3. The number of used lightning LED strips, irrigation pumps, and other operating electrical systems for electrical energy consumption is listed in Table 1.

Table 1. *Solar-powered sprouting room operating systems electrical power consumption.*

Sprouting room operating systems		Consumed energy; W	Used system units numbers	Operating period; h day^{-1}	Total consumed energy; kW.h day^{-1}	Total consumed energy; kW.h ton^{-1} (7 days)
1	Lightening LED strip (5 m length)	24	10	6; 9 and 12	1.44; 2.16 and 2.88	10.08; 15.12 and 20.16
2	Irrigation pump	3.6	7; 8 and 9	1	0.0252; 0.0288 and 0.0324	0.177; 0.202 and 0.227
3	Air cooler device 1, 2, 3 and 4 cooling units	63.75, 127.5, 191.25 and 255	1	24	1.53; 3.06; 4.59 and 6.12	10.71; 22.12; 32.13 and 42.84
4	Arduino controller	1.5	1	24	0.036	0.252
Consumed electrical energy in the solar-powered sprouting room					Maximum: 63.275 kW.h ton^{-1} Minimum: 21.219 kW.h ton^{-1}	
Consumed electrical energy in the traditional AC sprouting room					117.19 kW.h ton^{-1}	
Reduction ratio in the consumed energy					46.01 to 81.89%	

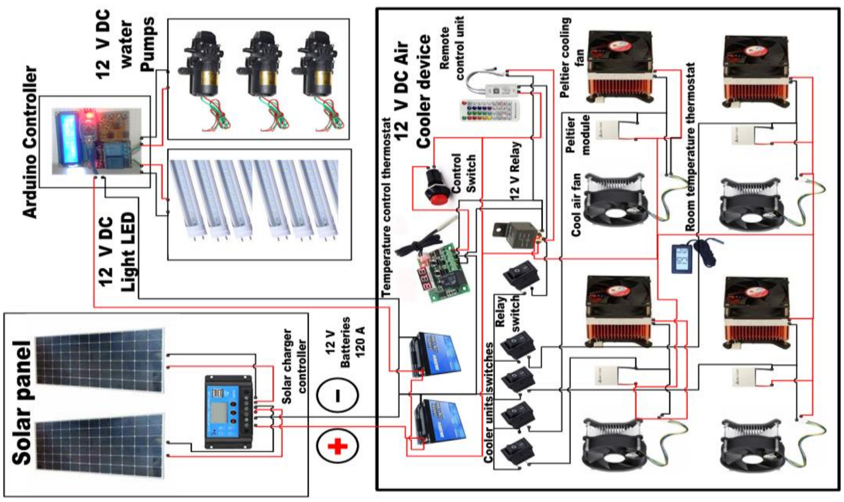

Figure 3. *Schematic drawing for the electrical circuit for the solar-powered sprouting room.*

Measurements

Air cooler device performance evaluation

Precise sensors were positioned throughout the sprouting chamber, over the barley sprouting trays, and between the racks to measure the temperature distribution therein. A data logging system allowed for real-time monitoring and continuous temperature recording. The cooling load was determined according to Equation 1. (Remeli *et al.*, 2020)

$$Q = \mathrm{UA}(T_o - T_i) + Q_{int} + Q_{sol} + Q_{vent} \quad (1)$$

$$Q_{vent} = \rho \times \mathrm{Cp} \times \mathrm{V} \times (T_o - T_i) \quad (2)$$

Where: Q is the total cooling load in Watt; U is the overall heat transfer coefficient W $m^{-2}K^{-1}$; A is the cooling surface area in m^2; T_i is the desired room temperature in °C; T_o is the outside temperature in °C; Q_{int} is the internal gain heat, W; Q_{sol} is the gain solar heat, W; Q_{vent} is the ventilation heat gains or losses due to air changes, W; ρ is the density of air, 1.225 kg m^{-3} at sea level; Cp is the specific heat capacity of air 1005 J kg^{-1}°C^{-1}; V is the volume of exchanged air, m^3 h^{-1}.

The energy efficiency ratio (*EER*) for the developed DC air cooler device was estimated as presented in Equation 3.

$$EER = \frac{q_c}{E} \quad (3)$$

Where: q_c is the output cooling energy, Btu; E is the electrical energy consumption Watt-hour; Wh.

The coefficient of performance (*COP*) of the peltier air cooling units was determined from Equation 4 (Parmar *et al.*, 2022).

$$COP = \frac{Q_c}{P_{el}} \quad (4)$$

Where: Q_c is the heat absorbed on the cold side, Btu; P_{el} is the input power, kW.

Lighting Intensity LI (lux):

Using a calibrated spectrometer, lighting intensity, expressed in lux, measures the quantity of light that reaches a surface inside the cultivation area, according to Grubisic *et al.* (2018).

Lighting Uniformity LU (%):

The cultivation area's uniformity of light distribution is evaluated by lighting uniformity. The coefficient of variation (CV), which is determined by dividing the standard deviation by the mean of light intensity as given in Equation (5), is used to quantify the lighting uniformity percentage, according to Asiabanpour *et al.* (2018).

$$CV = \frac{\sigma}{\mu} \times 100\% \quad (5)$$

Where: σ is the standard deviation of light intensity measurements; μ is the mean of light intensity measurements; and CV is the coefficient of variation, expressed as a percentage.

Vegetative characteristics of barely sprouted yield

Following an 8-day seeding period, the freshly sprouted barley was harvested, and measurements were taken of the root and shoot lengths (cm), total fresh and dry yields (kg m^{-2} and kg m^{-2}), the conversion factor (kg kg^{-1}) [the ratio of the produced yield to the initial planted seed weight], and chlorophyll content (mg m^{-2}). A digital atLEAF model chlorophyll meter was used to measure the amount of chlorophyll.

Chemical and quality analysis of barely sprout yield

Fresh samples (leaves and roots) were gathered, weighted, and oven-dried for 48 hours at 70°C in an air-forced oven before being stored for chemical analysis. As per Jones and Case (1990), powdered dried samples were digested in H_2SO_4 to identify their nitrogen content, which was then calculated using the Kjeldahl method. N was multiplied by 5.83 to determine the crude protein (Merrill and Watt, 1955). Samples were burned for four hours at 550 °C in a muffle furnace (Protherm, PFL 110/10 MODEL), according to AOAC (1990) to ascertain the amount of ash. Flame photometry was used to determine potassium (Ryan 1996).

Productive (P), ton

The productivity of the constructed solar-powered sprouting room per ton during the seven-day sprouting period was estimated in order to evaluate the efficacy of the system modifications.

Specific energy consumption (SE), kW.h ton^{-1}

The generated energy from the used solar panels was estimated for the sprouting room as presented in Equation 6 (Sharma and Puri, 2023). The electrical daily power consumption rates (kW.h day^{-1}) were determined for each operating system in the developed solar-powered sprouting rooms (cooling, lighting, and irrigation). Then, the total electrical power consumed during the production of 1 ton of sprouted barley over seven days was estimated as presented in Equation 7 (Hunt, 1983).

$$E = \mathrm{A} \times \mathrm{r} \times \mathrm{H} \times \mathrm{PR} \quad (6)$$

$$SE = \frac{\text{consumed power (kW.h)}}{\text{Productivity (Ton.h}^{-1})} \; kW.h\; ton^{-1} \quad (7)$$

Where: E = energy, kWh; A = total solar panel area, m^2; r = solar panel yield or efficiency; %; H = annual average solar radiation on titled panels (shaded, not included); PR = performance ratio (coefficient for losses) (0.75).

Cost economic analysis

The production cost (Pr. C) estimation for producing 1 ton from sprouted barley in the developed solar-powered sprouting room was determined as presented in Equation 8. The total operating costs, which included all production costs (grains cost + electrical power cost + repair and maintenance cost + interest cost + deprecation cost + taxes and insurance costs + labor costs + development price/10 years), were estimated. The production cost for the developed solar-powered sprouting room was compared with the traditional AC sprouting room before the development to calculate the cost reduction ratio (R.C) as presented in Equation 9. (Oida, 1997)

$$Pr.C = \frac{\text{Total operating costs USD}}{\text{Productivity ton}}\ USD\ ton^{-1} \quad (8)$$

$$R.C = \frac{Pr.C_2 - Pr.C_1}{Pr.C_2} \times 100 \quad (9)$$

Where: *R.C*= the cost reduction ratio, %; *Pr. C1&2*= the developed and traditional sprouting room production costs, USD ton^{-1}.

Profit net earn (NE) for the developed managed sprouting room was determined from Equation 10.

$$N\ E = \text{Total production costs per ton} - \text{production price per ton}\ \ USD \quad (10)$$

Statistical analysis

The experimental data was analyzed using Costat 2019, SPSS 2020, and Minitab 2020. An ANOVA was conducted to measure the interaction between the experimental variables and their effect on the selected measurements at a significance probability of $P < 0.05$. The least significant difference (LSD) was estimated at 0.05 for all variables. Linear regression analysis was performed to derive linear regression equations to determine the experimental variables that most influenced the measurements.

RESULTS AND DISCUSSION

Air cooler device performance evaluation

The forming units of the developed air cooler were tested before assembling the integrated electrical systems. The device was designed based on the cooling needs of the newly developed barley sprouting room. Figure 4 displays the effect of operating the number of cooling units in the developed air-cooling device and their impact on the sensing temperatures inside the sprouting room. There is a proportional relationship between the number of air-cooling units used and the sensing temperatures. The more cooling units are used, the smaller the difference between the perceived temperatures and the temperatures set by the digital thermo-controller.

The air cooler device was tested at four temperatures: 20, 21, 22, and 23 °C, which is considered the appropriate temperature range for the barley sprouting room, in agreement with Lin *et al.* (2009). There are five different types of temperatures measured inside the sprouting room. The sensing temperature (ST) is the mean temperature measured by a group of thermal sensors distributed within the room and connected to the data logger. The air cooler device sets a temperature CT that could be adjusted from 20 to 23 °C according to the needs of the sprouting room. The device thermostat temperature DT is measured by the built-in digital thermostat of the air cooler device. The ambient air temperature (RT) inside the sprouting room is the average temperature of the atmospheric air during the cooling process. The temperature over the barley trays (TRT) is the average temperature over the barley trays. The temperature between the sprouting tray racks (KT) is the average between the sprouting rack stands. When cooling units increase, there is a direct proportional relationship between DR, TR, TRT, and KT. The cooling efficiency increases exponentially when the temperature controller is set at 20 °C. The energy efficiency ratio of the developed air cooling device, EER, was measured at 1.76 when the device was fully operational, while the efficiency coefficient for the cooling units, COP, was 0.516.

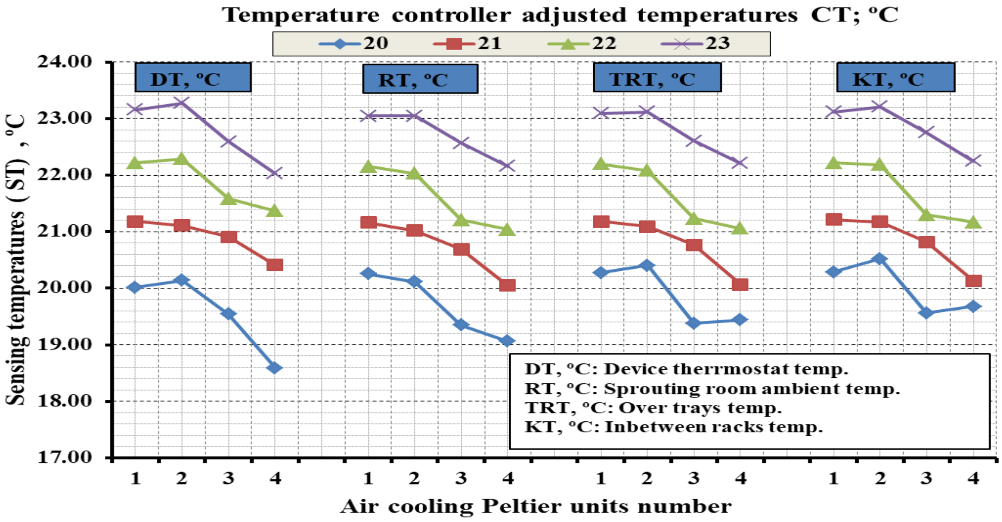

Figure 4. *The effect of air cooling Peltier units on the sensing temperatures in the solar-powered sprouting room.*

Table 2. *The different temperature differences inside the solar-powered sprouting room.*

CT °C	ΔDT °C				ΔRT °C			
AC units N.	1	2	3	4	1	2	3	4
20	+0.02	+0.14	-0.46	-1.41	+0.26	+0.11	-0.65	-0.4
21	+0.18	+0.11	-0.09	-0.59	+0.16	+0.02	-0.31	-0.95
22	+0.22	+0.29	-0.42	-0.63	+0.15	+0.03	-0.8	-0.96
23	+0.15	+0.27	-0.41	0.03	+0.05	-0.43	-0.43	-0.84
	ΔTRT °C				ΔKT °C			
20	+0.27	+0.4	-0.62	-0.56	+0.29	+0.52	-0.44	-0.32
21	+0.18	+0.09	-0.33	-0.93	+0.21	+0.18	-0.18	-0.87
22	+0.2	+0.08	-0.77	-0.94	+0.22	+0.19	-0.70	-0.83
23	+0.09	+0.12	-0.39	-0.79	+0.12	+0.21	-0.25	-0.75

Where: CT: temperature controller adjusted temperature°C; AC unit N.: the used air cooling units number; ΔDT °C: the difference between CT (thermocontroller temp.) and DT (device thermostat temp.); ΔRT °C: the difference between CT (thermocontroller temp.) and RT (ambient sprouting room temp.); ΔTRT °C: the difference between CT (thermocontroller temp.) and TRT (over sprouting trays temp.); ΔKT °C: the difference between CT (thermocontroller temp.) and KT (inbetween racks temp.).

As listed in Table 2, the cooling efficiency improves significantly when the cooling units used are increased by 3 and 4 units, respectively. The negative differences between the temperature differences at which the device was set show a significant improvement in of air cooling efficiency. This is due to the difference in the accuracy and sensitivity of the electronic components. All positive and negative differences did not exceed the correct ones for the temperatures. This is due to adjusting the current intensity, the voltage difference used, and the power needs of the cooling device at the standard level in agreement with Buchalik and Nowak (2022); He *et al.* (2024).

Lighting intensity and uniformity

Figure 5 shows the effect of the number of cooling units used at the lighting levels and irrigation rates tested on both the intensity and uniformity of lighting inside the solar-powered sprouting room. An inverse relationship exists between increasing the number of cooling units used and the intensity (LI) and uniformity (LU) of lighting at the lighting duration and irrigation rates. Figure 5A shows the lowest values of LI, 1200, and 1266.67 lux, respectively, at the maximum number of cooling units used for the advanced air cooler C4, at L 6h and I 2 m^3 ton^{-1}. The maximum values of LI were 2201.0 and 2178.78 lux at the lowest number of C1, the highest lighting duration was 12 h, and the lowest I was 1.7 m^3 ton^{-1}. Figure 5B shows a direct proportional relationship between the number of cooling units and the lighting uniformity at different lighting durations and irrigation rates. The highest LU 87.67 and 87.66%, values were recorded at C4, L 12h, and I 1.7 m^3 ton^{-1}. The lowest values for LU were 74.33 and 75.0%, respectively, at C1, L 6h, and I 2 m^3 ton^{-1}. Statistically, there was high significance at $P < 0.05$ for both LI and LU, respectively, for the interaction between the levels of the experimental variables tested. Linear regression Equations (11&12) for Li and LU show the gradual effect of the number of cooling units, lighting durations, and irrigation rates on the averages of the inferred values, as shown in Figure 6 A&B.

$$[LI, lux] = -146.273[C\ No.] + 98.757[L, h] + 635.674\ [I, m^3\ ton^{-1}] \quad R^2= 0.878 \qquad (11)$$

$$[LU, \%] = 3.113[C\ No.]+1.560[L, h] + 31.980\ [I, m^3\ ton^{-1}] \quad R^2= 0.894 \qquad (12)$$

The greater the number of cooling units, the more it affects the consumption of electrical energy and leads to a relative reduction in the intensity and uniformity of the lighting diffusion without affecting the productivity and quality of the sprouted barley. The uniformity of lighting increases significantly with the increase in the operating time of the lighting as a result of the improvement in the luminance of the LED lamp strip with the rise in the operating time. The increase in uniformity of lighting increased directly with the increase in cooling units due to balancing the electrical system's consumption inside the sprouting room, in agreement with Nelson and Bugbee (2014). Proper thermal management strategies, periodic maintenance, and cleaning routines may help for a significant improvement in lighting performance, by Lee *et al.* (2021).

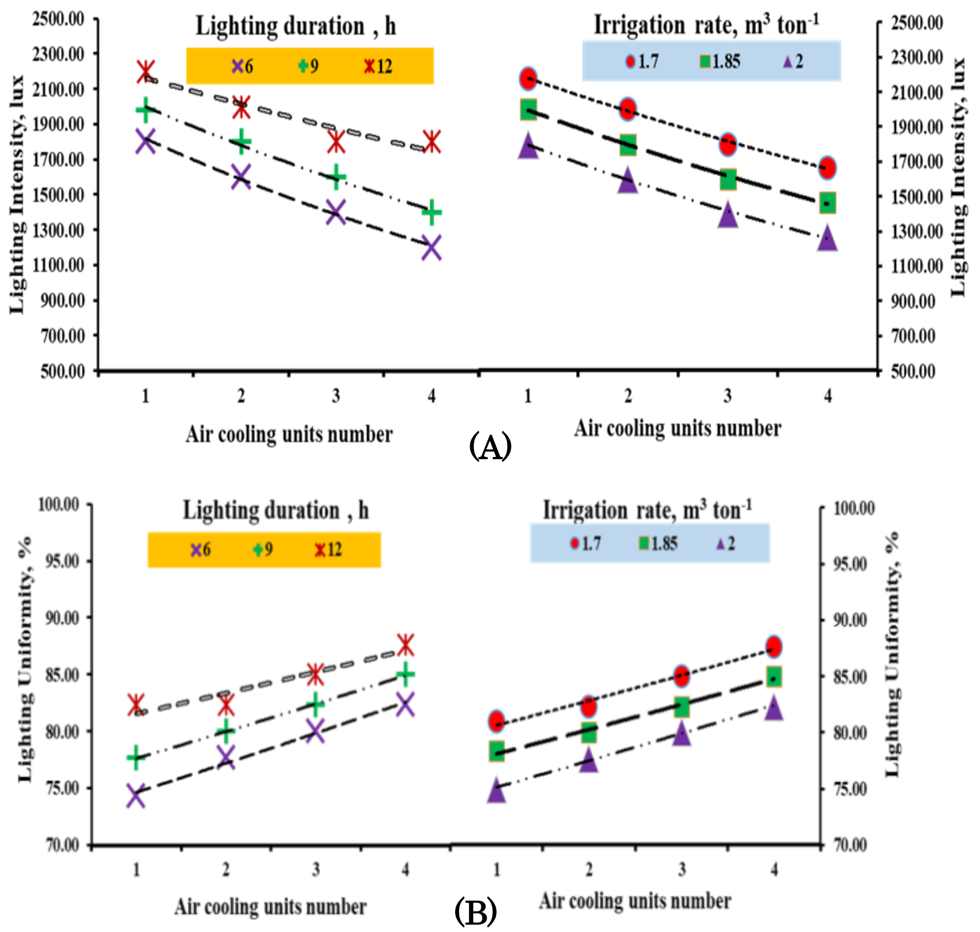

Figure 5. *The effect of air cooling units at the various lighting durations and irrigation rates on **(A)** lighting intensity and **(B)** lighting uniformity.*

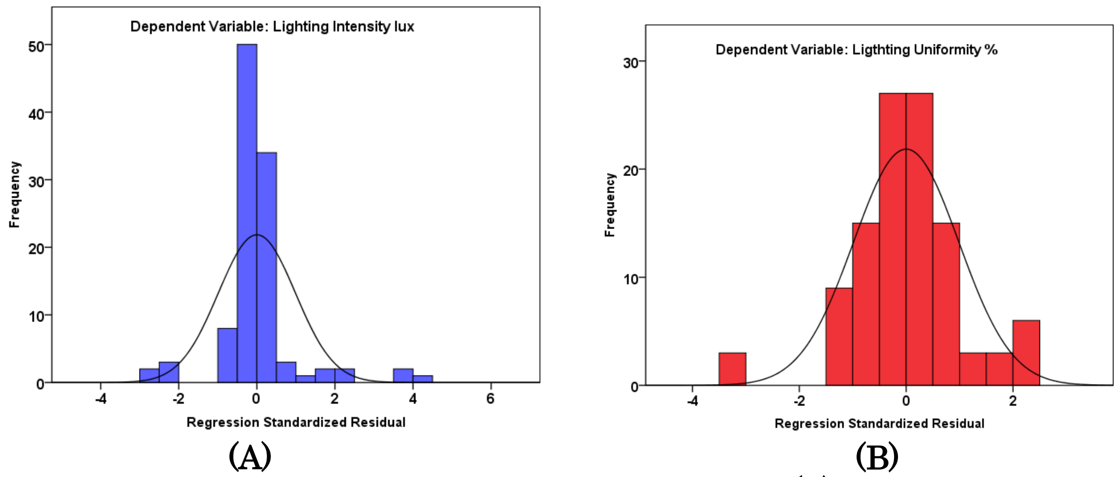

Figure 6. *Regression standardized residual frequency for **(A)** lighting intensity and **(B)** lighting uniformity.*

Sprouted barely vegetative characteristics

Table 3 presents the means and standard deviations for selected vegetative traits influenced by the studied factors, including the number of air cooling units, lighting duration, and irrigation rates, along with a control group. Increasing the number of air cooling units, lighting durations, and irrigation rates led to significant improvements in vegetative characteristics for the solar-powered sprouting room over the control room. The maximal root and shoot lengths (8.86 and 22.83 cm) were estimated at C4, L3, and I3 with an increment ration over the control of 40.90 and 23.65%, respectively. The highest fresh and dry yield mean values were 33.32 and 7.86 kg m^{-2}, which were estimated at the highest levels of C, L, and I, respectively, with increment ratios over control at 32.32 and 47.58%, respectively. The maximum conversation factor of 8.52 kg kg^{-1} was recorded for the maximum studied factor levels with an increment ratio over control with 39.91%. The maximum measured chlorophyll content was 40.18 mg m^{-2}, recorded for the maximum C, L, and I with an increment ratio of 14.88% over the control.

Statistically, the measured measurements had a high significant probability with the interaction with the studied variables at $P < 0.05$, as listed in Table 3. The results of the vegetative characteristics were because higher levels of cooling provided by additional Peltier modules positively impacted the growth and productivity of barley sprouts. Longer exposure to light positively affected the growth and development of barley sprouts, leading to enhanced productivity. Higher irrigation water rates facilitated better growth and productivity of barley sprouts, potentially by providing optimal hydration and nutrient uptake, in agreement with Farghaly *et al.* (2019). Overall, the results demonstrate the significant influence of the studied factors on the vegetative characteristics of barley sprout yield. The findings underscore the importance of optimizing environmental conditions, such as cooling, lighting, and irrigation, to maximize the productivity and quality of barley sprouts, thereby contributing to the advancement of sprout production techniques, in agreement with Elsoury *et al.* (2015).

Table 3. *Means and standard deviations for sprouted barely vegetative characteristics.*

Factors		Root length, cm	Shoot length, cm	Fresh yield, kg m^{-2}	Dry yield, kg m^{-2}	Conversion factor, kg kg^{-1}	Chlorophyll content, mg m^{-2}
Air cooling units No.	C_1	7.14± .97^a	15.14±1.44^a	24.53±2.10^a	4.67±0.32^a	5.80±0.23^a	36.98±0.78^a
	C_2	7.71± .19^b	16.99±1.34^b	28.48±1.60^b	5.65±0.19^b	6.74±0.33^b	38.59±0.97^b
	C_3	8.60±0.90^c	19.31±1.73^c	31.72±2.37^c	6.95±0.44^c	7.46±0.23^c	39.47±0.53^c
	C_4	8.11±1.29^d	22.83±2.19^d	33.32±2.64^d	7.86±0.14^d	8.52±0.26^d	40.18±0.44^d
LSD 0.05		0.160	0.136	0.124	0.056	0.057	0.079
Lighting durations, h	L_1	7.22±1.54^a	17.14±3.14^a	28.17±4.36^a	6.03±1.30^a	6.84±1.03^a	38.35±1.51^a
	L_2	8.17±0.88^a	18.49±2.71^b	29.53±4.05^b	6.26±1.20^b	7.15±1.01^b	38.69±1.36^b
	L_3	8.28±0.80^b	20.06±3.53^c	30.84±3.22^c	6.56±1.25^c	7.39±1.03^c	39.37±1.10^c
LSD 0.05		0.138	0.117	0.107	0.049	0.050	0.069
Irrigation rates, m^3 ton^{-1}	I_1	7.20±1.20^a	17.43±3.20^a	27.40±2.86^a	6.16±1.26^a	7.04±1.05^a	38.23±1.41^a
	I_2	7.78±0.92^b	18.58±3.23^b	30.08±4.09^b	6.31±1.26^b	7.13±1.05^b	38.94±1.36^b
	I_3	8.68±1.02^c	19.69±3.28^c	31.07±4.14^c	6.38±1.27^c	7.22±1.03^c	39.24±1.23^c
LSD 0.05		0.138	0.117	0.107	0.049	0.050	0.069
Control		5.13±1.03	17.43±3.20	22.55±2.94	4.12±0.31	5.12±0.17	34.20±0.32
R^2		0.860	0.896	0.898	0.895	0.893	0.893
P< 0.05		0.00***	0.00***	0.00***	0.00***	0.00***	0.00***

$^{a-d}$ the means with no common subscript within each column differed significantly ($P \leq 0.05$)

Sprouted barely chemical and quality vegetative analysis

The studied factors, including the number of air-cooling units, lighting duration, and irrigation rates significantly influenced the chemical and quality analysis of sprouted barley. Table 4 presents the mean values and standard deviations for nitrogen (N), phosphorus (P), potassium (K), and protein content across different experimental conditions. Also, Figure 7 demonstrates the interaction effect between the studied variables on the sprouted barley chemical analysis. As shown in Figure 7 (A&B) and Table 2, the maximum mean values for N, P, K, and protein content were 3.55, 0.84, 1.83, and 20.67%, respectively, with increment ratios over control of 11.55, 25.0, 7.10, and 12.87%. Statistically, there was a high significant probability for the measured chemical and quality measurements at $P < 0.05$, as listed in Table 4. The results obtained for the chemical and quality analyses were because greater cooling capacity, lighting durations, and irrigation rates positively impact the nutrient uptake and synthesis processes in barley sprouts, resulting in higher nutrient content in the harvested sprouts, in agreement with Bakeer *et al.* (2015); Wang *et al.* (2023).

Table 4. *Means and standard deviations for sprouted barely chemical analysis.*

Factors		N, %	P, %	K, %	Protein content %
Air cooling units No.	C_1	3.34±0.09[a]	0.64±0.02[a]	1.73±0.01[a]	19.48±0.52[a]
	C_2	3.39±0.03[b]	0.70±0.02[b]	1.77±0.02[b]	19.79±0.15[b]
	C_3	3.46±0.02[c]	0.78±0.02[c]	1.78±0.01[c]	20.19±0.11[c]
	C_4	3.55±0.03[d]	0.84±0.02[d]	1.83±0.03[d]	20.67±0.15[d]
LSD 0.05		0.0226	0.0044	0.0074	0.132
Lighting duratiosn, h	L_1	3.40±0.10[a]	0.72±0.08[a]	1.76±0.04[a]	19.83±0.58[a]
	L_2	3.45±0.08[a]	0.74±0.08[b]	1.78±0.04[b]	20.09±0.48[a]
	L_3	3.46±0.08[b]	0.76±0.08[c]	1.79±0.04[c]	20.16±0.47[b]
LSD 0.05		0.0017	0.0038	0.0064	0.114
Irrigation rates, m^3 ton^{-1}	I_1	3.43±0.10[a]	0.73±0.08[a]	1.77±0.04[a]	19.98±0.56[a]
	I_2	3.44±0.09[a]	0.74±0.08[b]	1.78±0.04[a]	20.03±0.53[a]
	I_3	3.44±0.09[a]	0.75±0.08[c]	1.78±0.04[b]	20.07±0.50[a]
LSD 0.05		0.0017	0.0038	0.0064	0.114
Control		3.04±0.05	0.63 ±0.01	1.70±0.01	18.01±0.21
R^2		0.859	0.893	0.825	0.859
P< 0.05		0.00***	0.00***	0.00***	0.00***

[a-d] the means with no common subscript within each column differed significantly (P≤0.05).

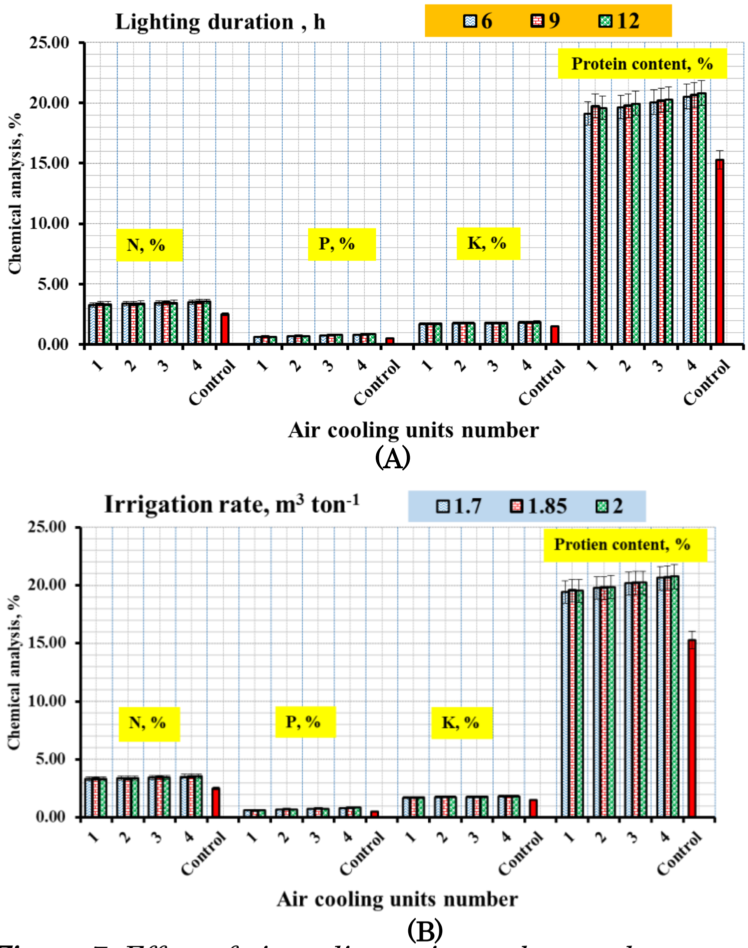

Figure 7. *Effect of air cooling unit number on the sprouted barley chemical analysis at* ***(A)*** *lighting durations and* ***(B)*** *irrigation rates.*

The solar-powered sprouting room productivity

Figure 8 shows the effect of the number of cooling units C on the productivity P of the solar-powered sprouting room and control (*the sprouting room operated by alternating current before modification)* at different lighting durations L and different irrigation rates I. There is a direct proportional relationship between increasing the number of cooling units and productivity when increasing lighting durations and irrigation rates. The lowest productivity recorded for the sprouted barley crop at the end of the sprouting cycle after seven days in the solar-powered room was 0.91 and 0.94 tons at C 1, L 6 h, and I 1.7 $m^3 ton^{-1}$, as shown in Figure 8. The highest values of P were 1.22 and 1.21 tons, respectively, at the highest number of air cooling units (C4), the highest lighting duration (12 h), and the highest irrigation rate (2 m^3 ton^{-1}). The maximum productivity of the control was 0.83 tons when using the AC-managed sprouting room before modification. The control productivity decreased by 31.97% compared to the maximum productivity of the solar-powered room. Significantly higher productivity rates were achieved compared to the control due to controlling all optimal production factors for barley sprouting, including cooling, lighting, and irrigation, in agreement with Ahamed *et al.* (2023). Statistically, there is a high significance $P < 0.05$ for the interaction between C, L, and I and their effect on P, as shown in the regression linear Equation (13), which shows the significance of the interaction between the levels of the experimental variables tested.

$$[P, ton] = 0.0905\ [C\ No.] + 0.0142\ [l, h] + 0.399\ [I\ m^3\ ton^{-1}] \qquad R^2 = 0.898 \qquad (13)$$

Figure 8C shows the regression line between the observed and expected values of productivity, which shows a significant increase in productivity for the solar culture room due to the development of cooling, lighting, and irrigation systems compared to the room before the modification. The data reveal notable enhancements in productivity across all configurations, indicating the efficacy of employing multiple Peltier modules in augmenting agricultural output. The significant productivity improvements underscore the effectiveness of the development interventions implemented within the system. These improvements may encompass various enhancements, including optimizing energy utilization, refining environmental conditions, and augmentation of growth-promoting factors facilitated by the Peltier modules. The escalating trend in productivity improvement with increasing Peltier modules suggests a positive correlation between system scalability and productivity. Scaling up the number of modules likely enables more efficient utilization of resources, finer control over environmental parameters, and better adaptation to varying cultivation needs, thereby resulting in amplified productivity enhancements. These findings affirm the potential of Peltier-based systems as a viable approach for enhancing agricultural productivity (Remeli *et al.*, 2020). Moreover, they underscore the importance of strategic system design and development to unlock the full potential of such technologies in agricultural contexts. The positive correlation between irrigation water usage rates and productivity levels suggests that achieving an optimal balance in water application is crucial for maximizing agricultural output while minimizing resource waste (Elzanaty *et al.*, 2021).

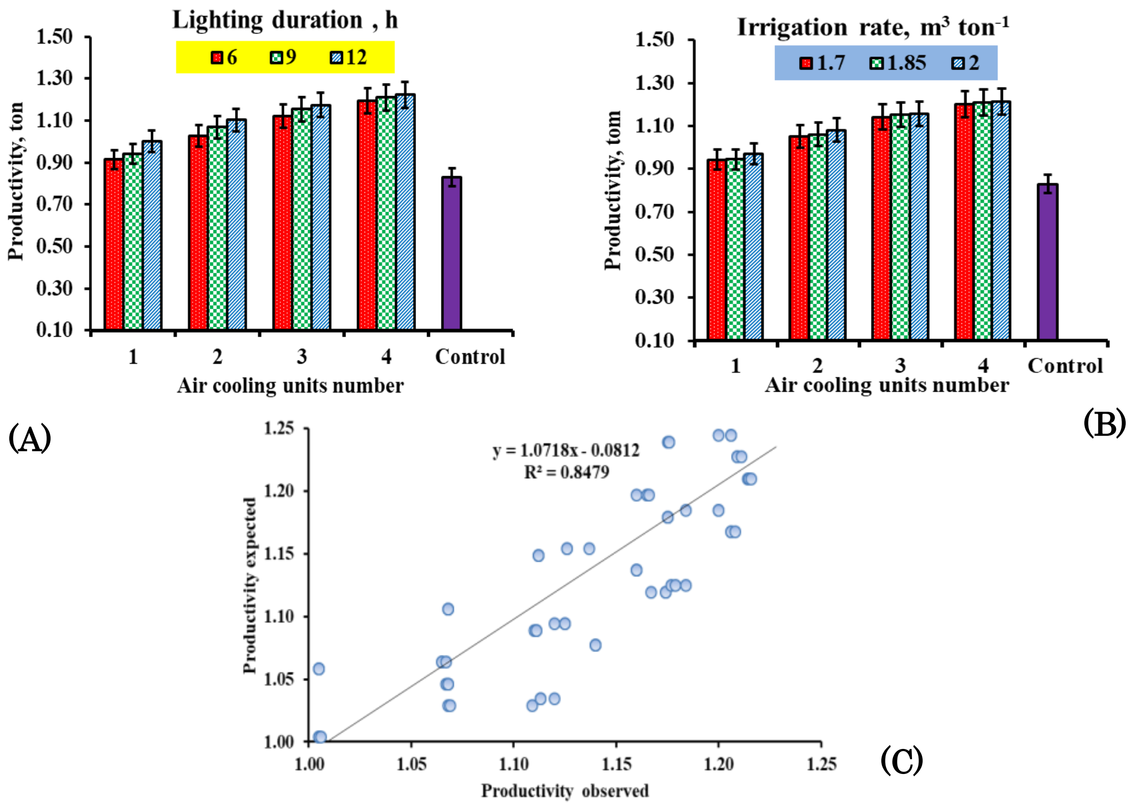

Figure 8. *Effect of air cooling unit number on the solar-powered sprouting room productivity at* ***(A)*** *the lighting durations,* ***(B)*** *the irrigation rates, and* ***(C)*** *the productivity observed and expected values.*

Solar-powered sprouting room-specific power consumption

Figure 9 shows the effect of the number of cooling units used for the developed air-cooling device and its impact on electrical energy consumption rates (SE) at the lighting durations used and irrigation rates. A direct, proportional relationship exists between the number of air cooling units used and SE at (C, L, and I). The greater the number of air cooling units used, the higher the rates of electrical energy consumption. As the duration of the lighting operation increases with the increase in irrigation rates, this leads to an increase in the rate of energy consumed, as shown in Figure 9. There is a significant difference between the decrease in consumption rates of the solar-powered sprouting room and the control, as shown in Figure 9 (B and D). The maximum electrical energy rates consumed by the solar-powered sprouting room at C4, L 12h, and I 2 m^3 ton^{-1} were 63.37 and 58.35 kWh ton^{-1}, as shown in Figures 9 (A and B). The lowest levels of electrical energy consumed by the solar-powered sprouting room were 21.24 and 26.26 kWh.ton^{-1}, at the lowest values of C1, L12h, and I1.7 m^3 ton^{-1}, as in Figures 9 (B and D). The control rates for the room powered by alternating current increased to 117.19 kWh ton^{-1}, with an increment ratio of 45.93% over the maximum energy consumption rate in the solar-powered sprouting room. Statistically, all variables and their interaction were highly significant at $P < 0.05$. It also appears in the linear regression Equation (14) that the maximum factor that directly impacts the electrical energy consumption rates of the solar-powered sprouting room is the number of cooling units, followed by the lighting levels and irrigation rates for the experimental treatments.

$$[(SE), kWh\ ton^{-1}] = 10.642\ [C\ No.] + 1.675\ [L, h] + 0.440\ [I, m^3\ ton^{-1}]\quad R^2=0.899 \qquad (14)$$

The low energy levels consumed per ton of sprouted barley for the solar-powered room are due to the development of 12-volt DC cooling, lighting, and irrigation systems. The use of advanced cooling devices instead of air conditioning devices has had a strong positive impact on reducing electrical energy consumption rates, in agreement with Elmorsy *et al.* (2013). The developed lighting systems and water pumps that operate with direct current instead of traditional lighting systems (tube lamps) or large water pumps also led to a significant reduction in the rates of specific energy consumption per ton of sprouted barley, in agreement with the results of Afzalinia and Karimi (2020).

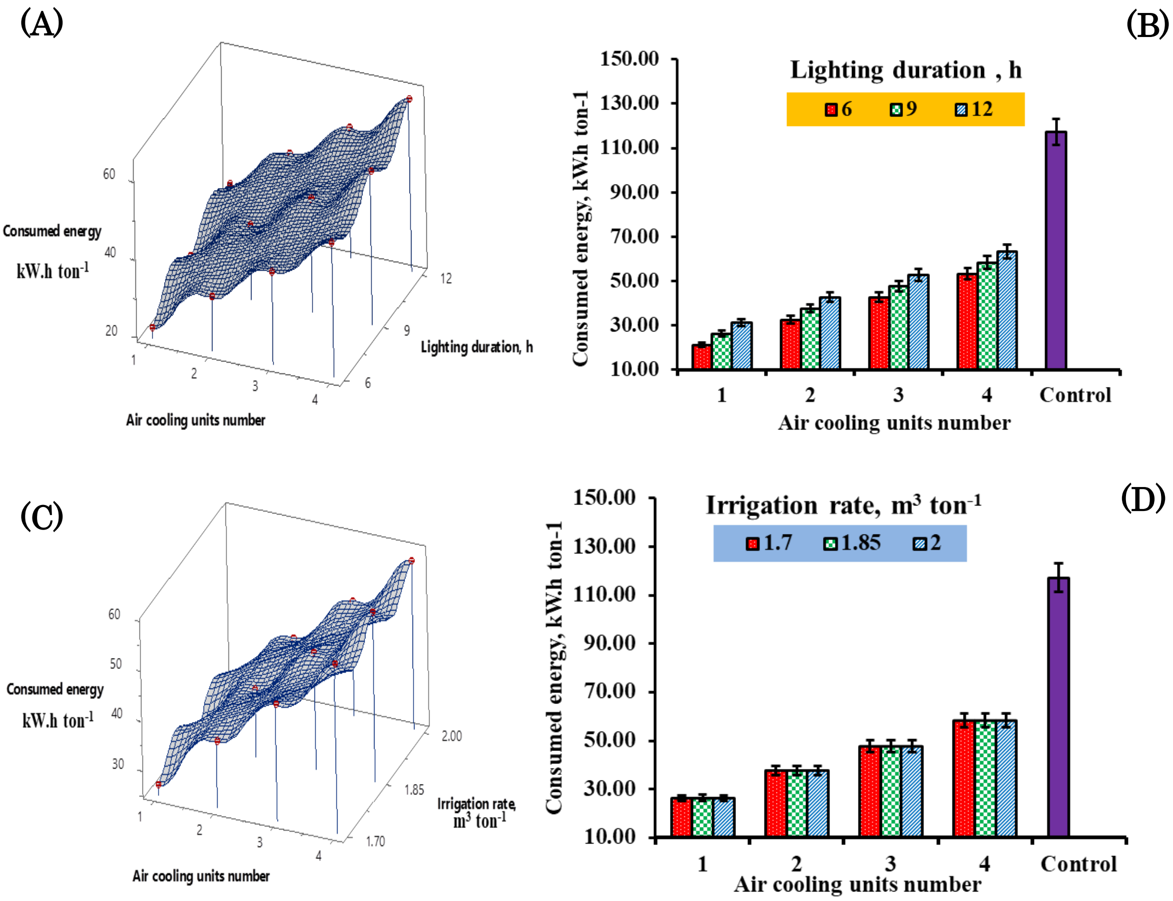

Figure 9. *Effect of air cooling units number on the consumed electrical energy for* ***(A&B)*** *the solar-powered and control sprouting rooms at the lighting durations and* ***(C&D)*** *the solar-powered and control sprouting rooms at the various irrigation rates.*

Financial economic analysis for the solar-powered sprouting room

Table 5 lists detailed mean average values of the production cost for the sprouted barley produced in the solar-powered and control sprouting rooms before modification. The cost of electrical energy per ton of sprouted barley decreased by 36.56% for the solar-powered room compared to the control room. The mean average price of the barley produced in the sprouting room was estimated after the germination cycle lasted one week for the experimental replicates. The price of the developed system, 14.67 USD for 10 years, was divided and added to the total costs of production to restore capital. There is a significant increase in net earnings of 33.32% compared to the control due to the lower cost of electrical energy and higher productivity within the same sprouting period, in agreement with Ghorbel and Kosum (2022). The ratio of electrical costs to total production costs was 3.77% for the solar-powered room compared with 8.56% for the control room, as listed in Table 5. The decrease in production costs is due to using solar energy instead of alternating current while replacing power-saver cooling, lighting, and irrigation systems. The production cost included the price of seeds and their treatments, maintenance costs, taxes, and the annual depreciation rate, in addition to labor wages, as demonstrated in Table 5. It could be recommended to acquire solar-powered barley sprouting rooms for animal production breeders to reduce production costs.

Table 5. *Mean and standard deviation of the economic analysis.*

xFactors		Electricity cost; USD ton^{-1}		Total costs; USD ton^{-1}	Barley price; USD ton^{-1}	Net earn; USD ton^{-1}
Air cooling units No.	1	0.84±0.13^{a}		35.59±0.13^{a}	60.34±2.69^{a}	9.75±2.58^{a}
	2	1.21±0.13^{b}		35.96±0.13^{b}	67.41±2.37^{b}	16.46±2.25^{b}
	3	1.53±0.13^{c}		36.28±0.13^{c}	72.84±1.45^{c}	21.56±1.33^{c}
	4	1.87±0.13^{d}		36.62±0.13^{d}	76.50±0.92^{d}	24.88±0.80^{d}
Lighting durations , h	6	1.20±0.39^{a}		35.95±0.39^{a}	67.36±6.79^{a}	16.41±6.41^{a}
	9	1.36±0.39^{b}		36.11±0.39^{b}	69.23±6.58^{b}	18.12±6.20^{b}
	12	1.52±0.39^{c}		36.27±0.39^{c}	71.22±5.39^{c}	19.96±5.01^{c}
Iririgation rates, m^{3} ton^{-1}	1.7	1.36±0.41^{a}		36.11±0.41^{a}	68.64±6.55^{a}	17.53±6.15^{a}
	1.85	1.36±0.41^{b}		36.11±0.41^{b}	69.15±6.76^{b}	18.04±6.36^{b}
	2	1.36±0.41^{c}		36.11±0.41^{c}	70.02±6.05^{c}	18.91±5.65^{c}
P value < 0.05		0.00***		0.00*	0.00***	0.00***
R^2		0.885		0.836	0.898	0.898
Mean value (solared)		**1.36±0.40**		**36.11±14.67**	**69.27±6.42**	**18.49±6.03**
Control (AC room)		**3.72±0.30**		**43.47±0.30**	**55.80±3.42**	**12.33±1.55**
Total develepment price	**146.70 USD**	**Solar system 50 USD**	**Air cooling devise 50.50 USD**	**Lighting system 10.5 USD**	**Irrigation system 20.5 USD**	**Arduino controller 15.2 USD**

Notice: USD equal 47.16 L.E during the experiments time. a-d the means with no common subscript within each column differed significantly (P≤0.05).

CONCLUSION

Developing a solar-powered sprouting room leads to achieving sustainable agricultural development. Utilizing the developed air cooling device, it achieved superior thermal adaptation in the solar-powered room. Increasing the operating air cooling units via air cooler devices significantly improved nutrient uptake and synthesis. Four cooling units with a lighting duration of 12 hours and an irrigation rate of 2 m^{3} ton^{-1} were the optimal production levels within the solar-powered sprouting room. Using the extended duration of 12 hours for lighting positively influenced the sprouted barley growth rate and productivity. Significant improvements in vegetative characteristics and chemical analysis were indicated for the sprouted barley in the developed sprouting room over the traditional AC-managed room before modification. The total electrical energy consumption rates for the solar-powered sprouting room decreased by 46.01% compared to the control, which led to a reduction in total production costs and an increase in the net profit of the developed system. Solar-powered sprouting rooms can be adopted as an excellent economical alternative to traditional greenhouses, suitable for remote areas and small livestock farmers.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ahmed Shawky El-Sayed: Design, conceptualization, methodology refinement, data collection, manuscript drafting.
AbdelGawad Saad: Methodology refinement, data analysis, manuscript review and editing.
Mohamed Ali Ibrahim Al-Rajhı: Methodology refinement, data analysis, manuscript review and editing.
Maisa Moneir Megahed: Guidance, economic evaluation, manuscript review for scientific rigor.

ETHICS COMMITTEE DECISION

This article does not require any ethical committee decision.

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