Chapter 12
Applications of Solar Energy for Enhancing Sustainable Food

Mohamed A. Eltawil, Mostafa M. Azam, and Maged Mohammed

Abstract The population is increasing worldwide and is expected to surpass 9 billion individuals by 2050, and at the same time, the global demand for food will increase dramatically and this will affect food security, which will negatively affect sustainable development. Recent developments in urbanization and Agricultural industrialization exerted pressure on agriculture, which played a crucial role in meeting the worldwide food demand. Adapting new and efficient methods for the sustainable agri-food sector is more crucial. The supply chain of agri-food mostly depends on fossil fuels which contribute to global warming and greenhouse gas emissions (GHGE). Several scenarios or strategies have been applied to minimize the GHGE by replacing renewable energy sources instead of fossil fuels. The utilization of solar energy technology is presently growing and has the potential to be incorporated into various agricultural industrialization activities. This has the ability to provide an alternative and sustainable solution in comparison to current practices. The aim of using solar energy advancements in the sustainable food industry is to help both society and agricultural communities in different areas and sizes improve their productivity and sustainability. This chapter addresses typical problems by introducing recent solar energy technologies that are utilized in drying systems, greenhouse cultivation, solar heating and solar refrigeration. The purpose of this chapter is to act as a guide

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M. A. Eltawil (✉) · M. M. Azam
Department of Agricultural Systems Engineering, College of Agricultural and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia
e-mail: meltawil@kfu.edu.sa; Mohamed.eltawil@agr.kfs.edu.eg

M. M. Azam
e-mail: mazam@kfu.edu.sa; mostafa.azam@agr.menofia.edu.eg

M. A. Eltawil
Department of Agricultural Engineering, Faculty of Agriculture, Kafrelsheikh University, Kafr El Sheikh 33516, Egypt

M. M. Azam · M. Mohammed
Department of Agricultural and Biosystems Engineering, Faculty of Agriculture, Menoufia University, Shebin El Koum 32514, Egypt
e-mail: memohammed@kfu.edu.sa

M. Mohammed
Date Palm Research Center of Excellence, King Faisal University, Al-Ahsa 31982, Saudi Arabia

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for scientists, engineers, and stakeholders who are dedicated to sustainability and are involved in projects concerning food security, energy, and climate change. Applying solar-based agriculture projects in Saudi Arabia, outlining the key challenges and benefits, and presenting them will bridge the gap in knowledge between producers and researchers in the field.

Keywords Sustainability · Fruits and vegetables · Greenhouse · Solar drying · Solar cooling · Photovoltaic

1 Introduction

It is important to monitor and decrease food waste during all stages of harvesting, handling, promotion, and distribution in order to guarantee sufficient access to food for the increasing global population. Improper handling procedures and storage facilities can cause the overall quality of food items to decrease. As a result of these issues, many developing countries experience significant losses in agricultural food production and related items. Postharvest losses in vegetables and fruits are estimated to account for 30% to 40% of the total production, significantly contributing to the rise in agricultural product prices (El-Sebaii and Shalaby 2022; Nukulwar and Tungikar 2021).

The intricate process of drying, which includes the exchange of mass and heat, is one of the primary methods employed to preserve agricultural produce. It requires a higher rate of energy, and as a result, scientists have undertaken extensive research to increase energy efficiency, accelerate the drying process, and maintain product quality. In recent times, the popularity of solar-powered dryers has increased because solar energy is an inexpensive and readily available source of power. Methods for storing thermal energy can enhance the dependability of solar energy for drying, allowing the utilization of stored energy when there is no solar exposure. Nevertheless, these experiments have incurred significant expenses due to the intricacy of every step involved in the solar drying process.

Multiple studies have supported utilizing advanced computer simulation tools to tackle this issue. These researches have yielded positive results and shown the efficiency of these techniques in various solar dryers. Hence, our objective in this chapter is to introduce parameters, examine different dryer types, and emphasize the significance and tactics for thermal energy storage (Barbosa et al. 2023).

The greenhouse industry is regarded as a sector that consumes a significant amount of energy and depends on fossil fuels, resulting in significant emissions of greenhouse gases (GHGs). Since the early 1960s, the global population has doubled and is projected to reach 9.8 billion by the year 2050. The worldwide problem of "Food Security," which is regarded as one of the most important sustainability factors, is made worse by this increase. Despite the fact that undernourishment is declining globally, hunger rates have been rising since 2014. Consequently, the number of individuals suffering from undernourishment grew from 784 million in 2015 to 821 million in 2017. Investments in the agricultural industry are required to provide food security, combat global hunger, and eradicate poverty. (Gorjian et al. 2020d; United Nations 2019). The "World Food Summit" (WFS) provided a comprehensive definition of food security in 1996, which was widely acknowledged as the following (Hassanien et al. 2016): "Food security is a situation in which all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life".

Based on the latest information from FAO in 2019, food systems globally use approximately 30% of the total energy utilized worldwide. Additionally, Around 19–29% of the annual greenhouse gas (GHG) emissions are caused by these systems' excessive reliance on fossil fuels. Agricultural greenhouse energy use has recently become a problem due to the increasing energy prices and environmental issues associated with the use of traditional energy sources. In order to lessen the reliance of greenhouses on non-renewable energy sources, the quest for alternate and clean energy sources as well as energy-saving technologies has been greatly encouraged (Marcelis and Heuvelink 2019).

Ensuring access to sufficient food is a difficult task in developing countries, even though there is a large amount of food being produced. This challenge may be due to significant losses that occur after crops are harvested, as well as uncertainty surrounding agricultural and food policies implemented by governments (Godfray et al. 2010; Munir et al. 2021). Consideration should be given to the seasonality of agricultural products in order to prevent spoiling. Certain fruits and vegetables are only available for a brief period each year and require special attention to avoid spoilage, particularly during storage. Post-harvest losses occur due to inadequate storage and transportation facilities on the farm, as well as frequent power outages during food processing and handling (Maphosa 2020).

The absence of facilities for processing crops after they are harvested at the farm level results in the deterioration of a considerable amount of perishable goods. To solve the issue of food security, it is imperative to address the loss that occurs after harvest. The cooling or freezing preservation method is utilized to effectively store perishable products at low temperatures in order to decrease microbial activity and prevent product deterioration and shrinkage. However, traditional cold storage systems require a high rate of energy for refrigeration. They are not frequently embraced by the farming community because of their excessive energy consumption. Furthermore, commercial cold storage facilities are only widely available in areas where grid electricity is accessible.

Solar energy can be used for cooling or refrigeration to preserve food. Utilizing solar energy for cooling is appealing because when there is a greater need for cooling, the sun is at its strongest. This, combined with the need to ensure thermal comfort for individuals residing in hot regions and the need for food preservation facilities, can serve as a motivating factor for further research and development in the field of solar cooling systems. The primary applications include vapor compression refrigeration, absorption refrigeration, and passive cooling. These applications may differ in terms of conditions, such as the use of continuous or intermittent cycles, energy storage on the hot or cold side, various control strategies, different temperature ranges of operation, and a range of collectors.

Reducing the losses that occur after the harvest of horticultural produce, which currently ranges from 25 to 30%, could significantly improve the availability of fruits and vegetables for consumers. Storage plays an important role in the handling of horticultural produce since it is constantly subjected to spoilage due to different endogenous and exogenous factors. The endogenous factors such as hormones, which are produced within the fruit itself, cause ripening and senescence. External factors such as the growth of microorganisms, temperature, relative humidity, air movement, and physical damage lead to significant losses in both the quality and quantity of the produce. The storage life can be prolonged by days, weeks, or even months by inhibiting these undesirable changes with either chemical treatments or modification of the storage environment. Refrigerated storage, which is one of the most effective methods for storing fruits and vegetables in their fresh state, is accessible in industrialized countries due to the presence of electricity. However, it is not readily available in the majority of the world.

The cold storage industry has developed rapidly in recent years. Despite the progress made, the industry has been facing numerous problems lately affecting its further growth. The major problems faced are inadequate supply of electricity, which is the basic raw material of the industry, uneconomical rentals fixed by different states, non-recognition as a priority industry, and denial of financial benefits at concessional rates, on electric tariffs. The primary technical issue with solar refrigeration is that the system relies heavily on environmental factors such as the temperature of the cooling water, air temperature, solar radiation, wind speed, and more. Conversely, its energy conversion efficiency is low.

Therefore, in the absence of a traditional energy source, the presence of vapor compression refrigerators connected to photovoltaic panels could offer a potential solution to this issue.

2 Some Solar Applications

2.1 Solar Drying Technologies

Energy plays a crucial role in the sustainable development and economic growth of every nation. The energy demand is increasing in almost every sector to achieve economic development. The recognition of the global energy crisis has motivated scientists and engineers to pursue the utilization of renewable energy in agriculture. The need for energy in all forms around the world is constantly increasing due to rapid industrial development. Fossil fuels, including those needed in the process of drying, continue to meet the majority of the world's energy needs (REN21 2018). Nevertheless, the adverse effects on the environment and the depletion of their resources significantly restrict their usage. Renewable energy sources have emerged as essential alternatives for attaining a more environmentally friendly and dependable energy future as a result of rising environmental consciousness and the implementation of sustainable energy policies (Achkari and Fadar 2020).

Solar energy is becoming popular due to having the highest energy potential out of all renewable sources, being cost-free, limitless, accessible, and diverse. Optimizing drying processes is important both economically and environmentally. The search for solar-powered dryers has gained popularity recently, with many countries still relying heavily on non-renewable energy sources (Bekkioui et al.. 2020). Despite the impending environmental impact, conventional fossil fuel-based dryers and kilns are still used. Solar dryers have numerous advantages over conventional kilns and dryers, in addition to their positive impact on the environment. They are easy to set up and use, can lower overall drying expenses by up to 80%, and encourage the production of higher-quality finished goods. Furthermore, they emit no greenhouse gases (Jain et al. 2023). Even though solar dryers have been shown to have positive economic and environmental effects, more studies should always be done to optimize solar energy's capture, conversion, and use. Optimizing solar energy-based dryers offers the potential for faster drying and more efficient use of energy, enabling a greater quantity of products to be dried.

One of the primary steps in the processing chain for farmers is drying, as noted by Ihediwa et al. (2022) and Ndukwu et al. (2022a, b). This process is used to either prepare products for further processing or extend their shelf life for storage. Regrettably, it has been found that the process of drying is a significant user of energy, making up 12–15% of energy usage in agriculture globally. (Catorze et al. 2022; Ihediwa et al. 2022, Samimi-Akhijahani and Arabhosseini 2018). Furthermore, it is reported that the process of drying necessitates anywhere from 6 to 30 times more energy in comparison to cooling or freezing. (Machala et al. 2022). Since fossil fuels are often utilized to provide the heat needed for drying, they also contribute significantly to carbon emissions (Ndukwu et al. 2023). Therefore, there is currently an increasing agreement to transition from dryers that rely on fuel to ones that are fueled by renewable energy sources" (Chowdhury et al. 2020; Kumar et al. 2023) to conserve the environment and its natural resources.

To achieve Sustainable Development Goals, clean technologies are being implemented across the entire energy spectrum, particularly in rural farming areas (Messina et al. 2022). These technologies aim to conserve resources, combat climate change, and reduce air pollution. The following list of renewable energy sources, as provided by Rahman et al. (2022), is as follows: "Geothermal energy, solar thermal energy, wind energy, and solar photovoltaic energy".

Reviews on solar drying can be categorized into a variety of subcategories. The use of thermal storage to accelerate drying, hybrid technologies, solar greenhouses, energy efficiency, exergy efficiency, economic evaluations, environmental evaluations (4E), software applications, crop quality attributes, and solar biomass drying are some of the topics covered in thorough reviews that cover every facet of solar drying research. The results of these evaluations are then critically analyzed, as shown in Fig. 1.

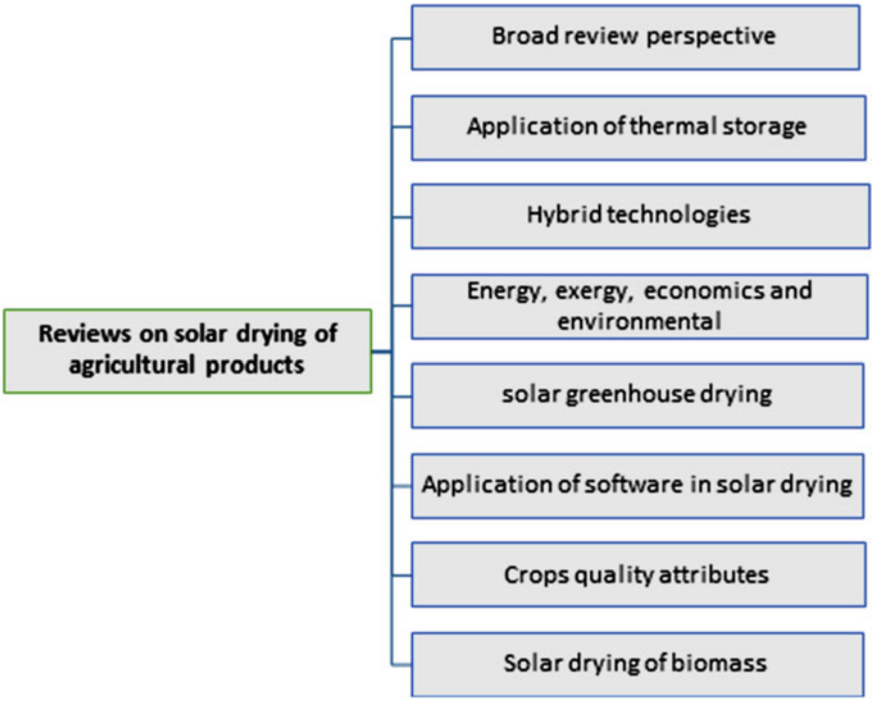


Fig. 1 Classification of thematic reviews for solar drying of agricultural products (Ndukwu et al. 2023)

Drying is a means of preserving food that involves extracting moisture from harvested goods to prevent the growth of microorganisms. Open sun drying is one of the oldest known methods for processing and preserving agricultural products, harnessing the sun's readily available and abundant energy. On the other hand, the agro-industry utilizes thermal processes for food processing and storage (Erkmen and Bozoglu 2016). Agricultural products can be solar-dried inside structures, which is an effective way to lessen quality loss and post-harvest losses that are common with conventional sun-drying methods. Advancements in sustainable growth have been made possible by the limitations of conventional energy sources and the benefits of solar energy, including its efficiency and cost-effectiveness. Solar radiation is globally available and has now replaced the conventional method of drying to preserve fruits and vegetables for longer periods. Food drying is a challenging process that involves irregularities in mass and heat transport as well as physical and chemical interactions that may have an impact on the product's quality. The adjustment and regulation of moisture levels in solid substances through drying is a crucial stage in the production of several types of chemical goods.

The field of food drying is diverse because different foods require various drying procedures. To remove excess water and increase the moisture content to the desired level, a product can be dried, whether it is natural or synthetic. This process requires a lot of energy to run. Foods usually have higher water contents than what is suitable for long-term storage, making it crucial to reduce their moisture levels. When food has less moisture, it takes longer for enzymes, bacteria, yeasts, and molds to form. This allows food to be preserved and stored for longer periods without going bad. Another example of drying food is removing all moisture until there is none left. Once the dried food is ready for use, it is rehydrated and takes on its original form (Izadi et al. 2022). A cost-effective strategy for preserving excess agricultural output is solar energy drying, particularly for crops grown in moderate to small quantities. It is environmentally friendly and is employed to dehydrate food items, agricultural products, and crops ranging from individual households to small businesses. Consequently, numerous solar drying techniques have been developed, such as direct, and indirect sun drying, and mixed-mode sun drying (Ndukwu et al. 2022a, b).

The use of artificial dryers results in an enhanced quality of dried products because it enables control over the drying air's velocity and temperature. However, these dryers also require a significant quantity of energy is required to warm and move the airflow, leading to increased capital and operational expenses (Janjai et al. 2009).

The diagram in Fig. 2 shows the different groups of solar dryers. This has greatly augmented the revenues of small agricultural farms and communities.

Phadke et al. (2015) identified two types of solar dryers: forced circulation dryers and natural circulation dryers. Sharma et al. (2021) stated that solar dryers can be categorized according to the method of air circulation or operation, the manner in which heat is transferred to the product, and the design of the dryer (Fig. 3).

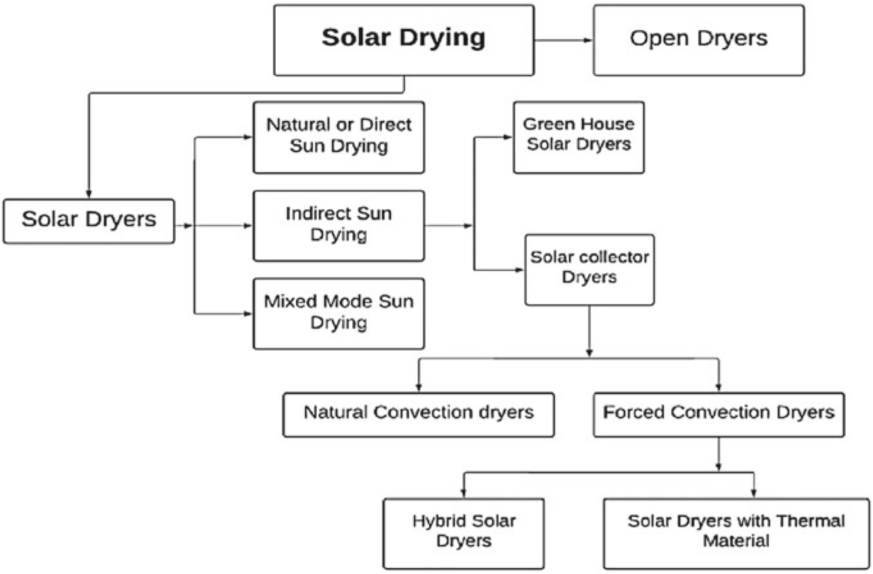


Fig. 2 Process classification for solar drying (Suresh et al. 2023)

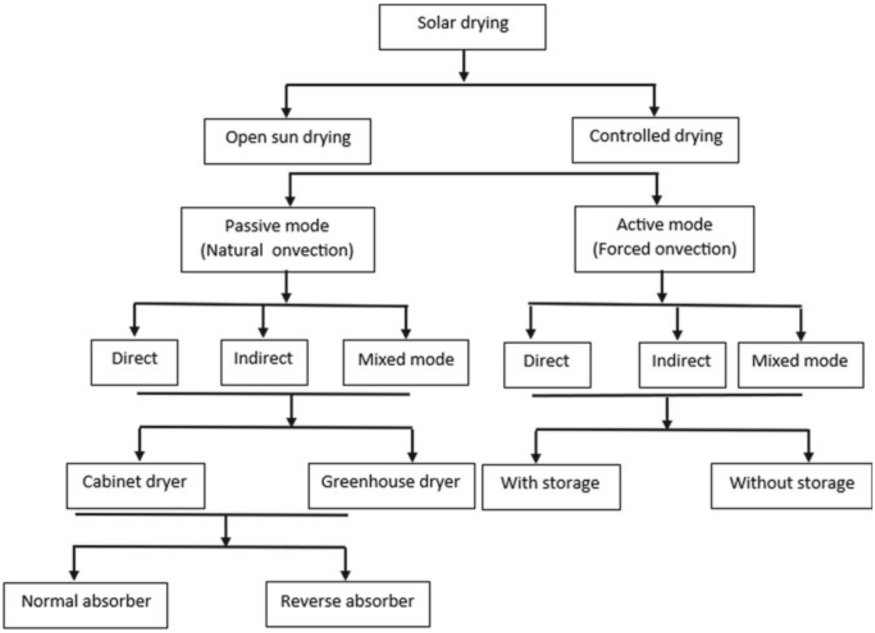


Fig. 3 Solar dryer classification (Sharma et al. 2021)

Direct solar *dryer*: The item that is supposed to be dried immediately absorbs sun energy. Hot air is provided by solar collectors and is used in the drying unit. Through a translucent sheet covering the east and west sides of the chamber, the product is exposed to solar energy. Due to direct solar exposure, this method has the potential to produce low-quality products with a black surface (Fig. 4).

Indirect solar dryer: The air that passes through the product being dried is heated by sun radiation in the system. Normally, solar radiation captured by separate solar collectors is converted into thermal energy and used to heat the air (Figs. 5 and 6). The sides of the drying chamber are insulated in this working mode to block solar radiation and simultaneously minimize heat loss through the sides (Eltawil et al. 2012).

Solar natural convection dryer: A temperature gradient causes the heated airflow. Due to the heated air's natural tendency to travel around, it is frequently referred to as a passive dryer. The addition of a chimney, where the exhausting air is heated even more, may improve the results of the solar dryer.

Forced convection dryer: "The air is pushed through a device that collects solar energy and the material being dried by a fan or blower, commonly known as an active dryer. Dryers with forced circulation typically result in quicker drying, increased airflow, and improved control over the temperature of the heated air. The dryer can

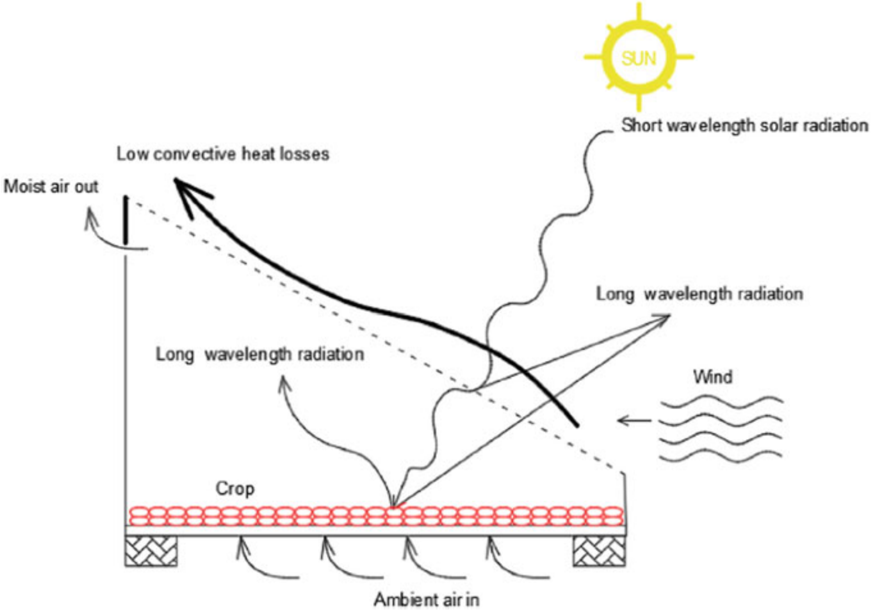


Fig. 4 Natural or direct solar drying process (Suresh et al. 2023)

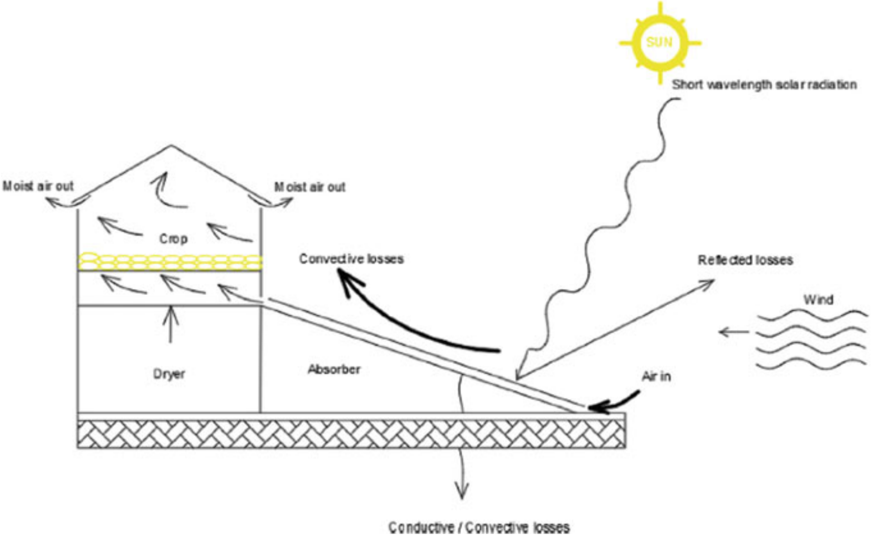


Fig. 5 Indirect solar dryer (cabinet–dryer) (Suresh et al. 2023)

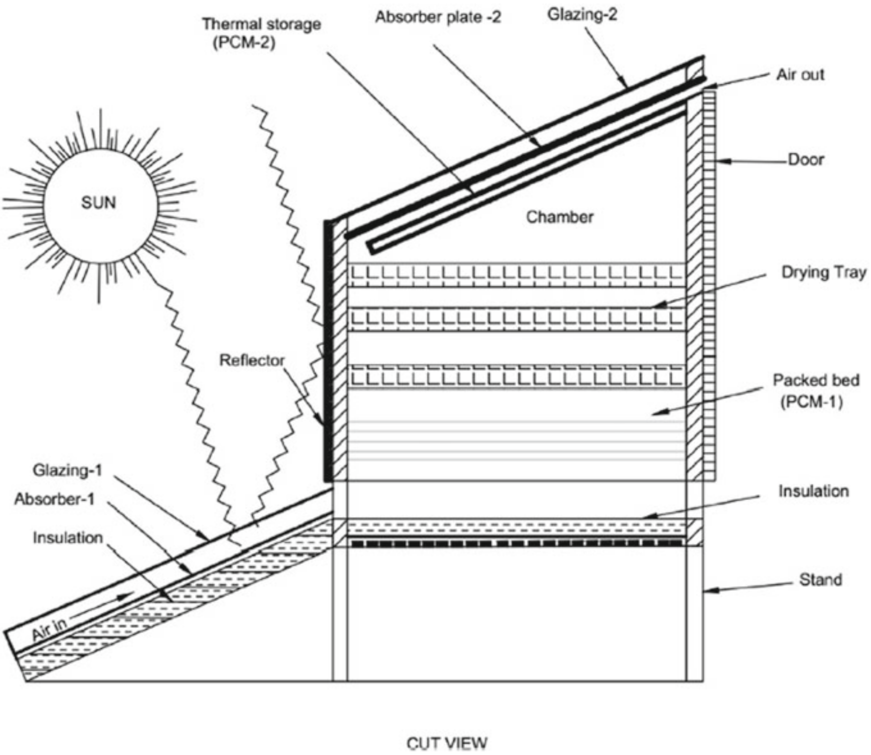


Fig. 6 Dryer with thermal storage (Chichango et al. 2023)

be customized to accommodate various volumes based on the user's requirements and the availability of open space".

Actually, the idea of forced or natural air circulation underlies the operation of these dryers. The mixed-mode natural convection solar crop dryer may be the most efficient, according to tests comparing these basic ideas. It performs especially well in humid tropical regions where the climate is ideal for drying agricultural items in the sun (Eltawil et al. 2012).

Due to the unreliable or nonexistent power supply in villages, natural convection solar dryers are favored over forced convection solar dryers for drying a variety of agricultural products at the farm level.

The benefits and drawbacks of various solar dryers, including natural, indirect, and mixed-mode drying methods, are listed in Table 1. This includes information about their construction level, dehydration rate, and economic factors.

Difficulties and Challenges

Figure 7 illustrates a number of factors that have an impact on the design, development, use, and assessment of solar dryer systems (Suresh et al. 2023) which include:

Table 1 The pros and cons of different solar dryers (adapted from Suresh et al. 2023)

S. No.	Type of the dryer	Pros	Cons
1	Natural or direct solar drying	• Easy construction, simple in loading/unloading • It protects the products to be dried • Agricultural produces can be dried during the night or in rainy conditions • The clear lid of the enclosure reduces produce contamination • The quality of the dried produces is better in comparison to sun drying outdoors	• The rodents, birds, and other animals may damage the products • The degradation occurs due to exposure to direct sun rays, rain, dust storms, and dampness • There is also pollution from undesirable weather parameters such as wind-borne debris, dirt, and dust • The damage can also result from excessive drying. Additionally, there may be insect infestations and the development of microbes • Furthermore, there are additional losses during storage due to uneven drying

(continued)

Table 1 (continued)

S. No.	Type of the dryer	Pros	Cons
2	Indirect solar drying	• The commodities to be dehydrated are slightly elevated and flat plate air solar collectors are used and achieved a higher dehydration performance • This method is suitable for small farms • The utilization of this method helps to avoid the contamination of the dried product • In comparison to the direct method, it is a solar drying technique that is substantially more effective • To maintain the quality of the product, exposure to direct solar radiation should be avoided • The drying time may vary depending on the product • The final condition of the product is not determined by natural phenomena	• High costs for construction • It needs maintenance after a certain time
3	Mixed mode sun drying	• Speed up the drying process while maintaining safe moisture levels • Compared to alternative drying methods, this method significantly reduces the required drying time	• The capacity of the dryer with agricultural food is very low • The quality of grain dried over a year is worse in comparison to grain dried utilizing an indirect dryer • The cost of maintenance is high • The capital expense is more

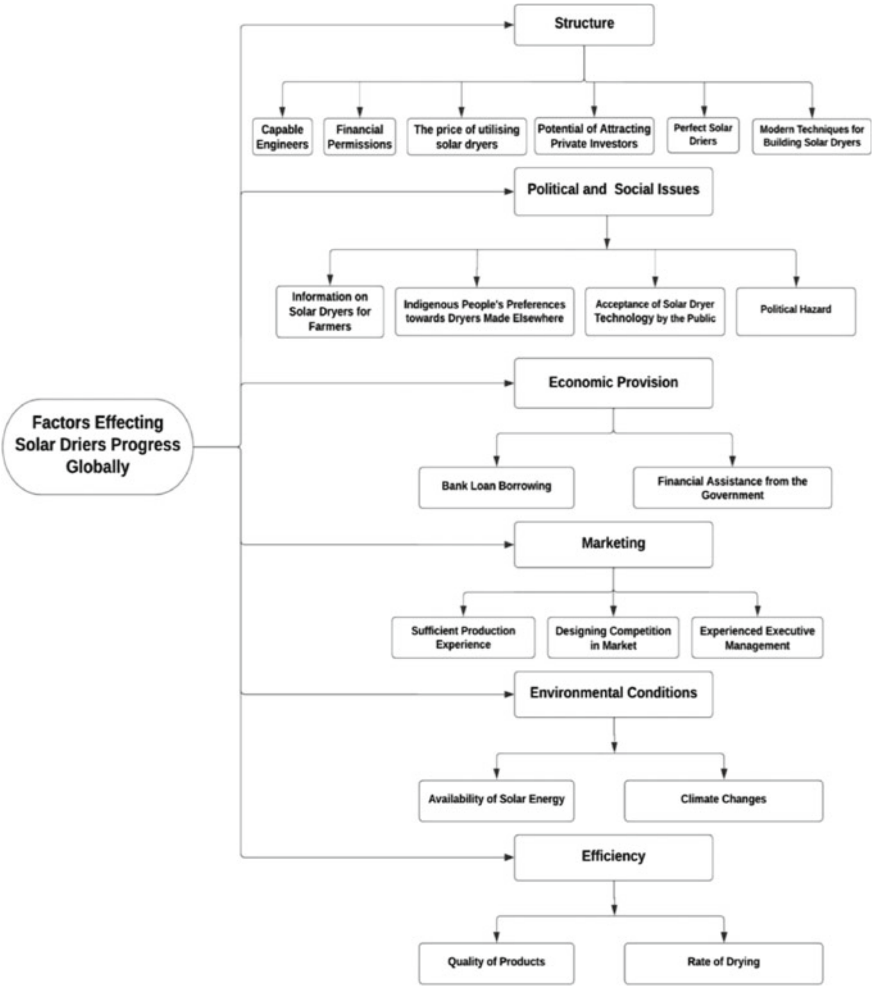


Fig. 7 Proposed factors that affect the solar dryers progress (Suresh et al. 2023)

(a) Structure (Khanlari et al. 2021; Sharma et al. 2009a, b; Solangi et al. 2011),
(b) Political and social issues (Benmarraze et al. 2015; Das and Parvathy 2022)
(c) Economic provision (Chandel et al. 2014)
(d) Marketing,
(e) Environmental condition (Das and Parvathy 2022)
(f) Knowledge and efficiency

2.1.1 Some Drying Applications:

The presence of a combination (direct/indirect) multi-tray product drying system connected to photovoltaic modules could offer a potential solution for preserving fruits/vegetable products and extending their storage duration. Eltawil and Imara (2005) designed a multi-tray and mixed-mode dryer that operated using a PV system. The designed system is suitable for rural areas. The experimental setup consisted of a solar PV module, battery, plastic solar collector, and multi-tray dryer structure fabricated and installed outdoors. Figure 8 shows an experimental multi-tray crop drying setup powered by solar photovoltaic (SPV).

Working principles: The warm air from the plastic solar collector is being pushed into the drying chamber from the bottom by a DC fan powered by an SPV (solar photovoltaic) panel. The crop receives heat from the air as it then contacts the first tray. Additionally enhancing the temperature of the crop directly, some of the solar radiation that strikes the front glazing also makes its way into the drying chamber. As a result, the dryer operates in a mixed mode. The item must be dried for two to four straight sunny days. Both batch mode and semi-continuous mode can be used to dry the product. Drying takes place from 8:00 AM to 6:00 PM. Three labeled samples were used to track the drying data. Each sample was weighed separately, then placed in the middle and on either side of each tray. When the samples' weight loss had almost come to an end, the dehydration process was paused.

To evaluate the drying system's effectiveness, a fig fruit (*Ficus carica*) was dried. The study examined three drying techniques: direct and indirect natural convection

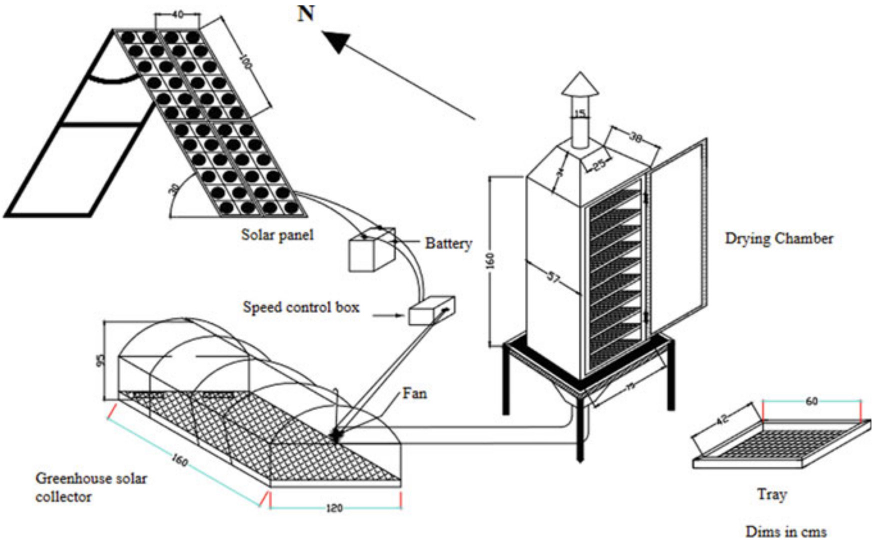


Fig. 8 Schematic diagram for SPV-powered multi-tray dehydration system for rural areas (Eltawil and Imara 2005)

drying, and drying in an electrical oven. Mixed mode forced dehydration with three distinct airflow rates (1.52, 2.15, and 3.25 m^3/min). For each treatment, the figs were treated differently, such as with 1% sodium hydroxide, 1.5% sodium metabisulfite in water, followed by drying, or drying following blanching-drying and soaking in a 70% sugar solution.

Results outcomes are summarized as follows (Eltawil and Imara 2005):

- The amount of sunlight that is being observed is sufficient to justify the investment in a mixed-mode multi-tray crop drying system that is operated by a SPV system outdoors. This system is particularly beneficial in remote areas.
- The recorded data shows that at 13:00, the average maximum power output of 139.35 W, and the corresponding average maximum insolation of 963.12 W/m^2 on the panel surface.
- It has been discovered that when the module temperature increases, the short-circuit current increases while the open-circuit voltage slightly decreases.
- The average daily PV conversion efficiency of 8.76% corresponding to an average panel temperature of 47.55 °C was recorded for clear sunny days. By 16.61 °C, the daily average panel temperature was greater than the outside temperature.
- On clear sunny days, a daily average PV conversion efficiency of 8.76% was found, which corresponds to an average panel temperature of 47.55 °C. Additionally, the average daily panel temperature was found to be 16.61 °C higher than the ambient temperature.
- For varied airflow rates of 1.52, 2.15, and 3.25 m^3/min, respectively, the average daily panel energy output of 1.28 kWh per day exceeded the daily load energy demand by 50.4, 44.3, and 39.61%.
- The maximum stagnation temperature attained in the dryer was 67.4 °C for an empty mixed mode natural convection dehydration system when the dryer outlet was closed. The results observed indicate that the obtained dryer temperature can be used for drying horticulture products since a drying temperature within the same range is needed.
- Under natural convection for an empty drying system (i.e. drying under shaded conditions) and the air outlet of the dryer was opened, the variation of temperature was limited to one degree.
- Under the batch mixed mode forced convection system, it was found that the highest and minimum values of air temperature inside the plastic solar collector and the dryer were recorded at airflow rates of 1.52 and 3.25, m^3/min, respectively. So, it is recommended to increase the area of the plastic solar air collector hence variation of air temperature inside the collector can be minimized.
- The best pretreatment for the dehydration of figs was with a 1.5% aqueous solution of sodium metabisulfite since it required the shortest dehydration time to reach the equilibrium and safe moisture content.
- Rehydration process revealed that the lowest and highest rehydration ratio was observed with pretreatments of 1% sodium hydroxide followed by 1.5% aqueous solution of sodium metabisulfite and 1.5% aqueous solution of sodium metabisulfite only, respectively.

- It has been possible to construct multiple regression equations that can be utilized to forecast SPV and other dehydration system performance.

Potato chips are highly popular fried snacks. Their distinctive crispy texture is one of the most crucial factors determining the quality of the final product. This texture is primarily influenced by the quality of the raw materials and the parameters used in the technological processing (Kita 2002). The temperature at which frying is done and the type of oil used have a known impact on the dried potato crisps. Decreasing the frying temperature can be beneficial in preventing certain negative qualities like the creation of acrylamides, which are known to potentially be cancer-causing substances (Gertz and Klostermann 2002).

Peppermint oil is a highly popular and commonly used essential oil due to its key components: menthol and menthone. It finds applications in flavoring pharmaceuticals and oral preparations. Consequently, the appropriate method of conserving peppermint through dehydration is crucial in preserving its properties.

A solar cabinet dryer (SCD) that combines solar and wind energy was conceived, manufactured, and tested by Eltawil et al. (2012) to dry horticulture items and medicinal herbs. To improve the airflow, they added a flat plate solar collector and a vertical solar chimney that had been blackened. To further enhance the circulation, they added a suction axial fan that was powered by wind. The researchers evaluated the performance of the SCD with and without a load, using potato chips and peppermint as examples. To compare results, they also dried the products separately using traditional methods: open sun drying, the SCD, and an electric oven.

Passive solar cabinet dryer: A solar collector is used to capture solar energy, which is then directed into the cabinet in the solar cabinet dryer. The heated air is then used to heat a larger volume of air, which is then moved by natural convection through a drying chamber. As a result, the product receives direct and indirect heating from the sun's light. As shown in Fig. 9, this solar dryer was created, built, and assembled. A solar cabinet, a flat plate solar collector, air vents, and dryer stands are some of its numerous parts. A hardwood drying chamber, two shallow perforated trays made of 0.5 cm mesh stainless steel wire screen stacked one on top of the other, a clear glass cover (5 mm thick glass sheet), and a chimney equipped with a suction axial fan that can be powered by wind are all parts of the solar cabinet drier. A flat plate solar collector is connected to the cabinet drying chamber at the bottom (plenum chamber) from the front side. The front glazing of the cabinet allows some sun radiation to enter the drying chamber, raising the warmth of the crop even further. As a result, the dryer operates as a mixed mode type by fusing components from both direct and indirect solar drying systems.

The top of the cabinet drying chamber was connected to a vertical cylindrical solar chimney that was constructed of galvanized iron and painted matte black. Convectional airflow was facilitated and controlled. Through natural convection, this design increases airflow throughout the entire building by reducing the density of the air in the chimney. The solar chimney was equipped with an axial fan to improve airflow even further. This fan uses wind energy to run, which produces a suction effect. The suction fan was driven by a little windmill. The chimney's center

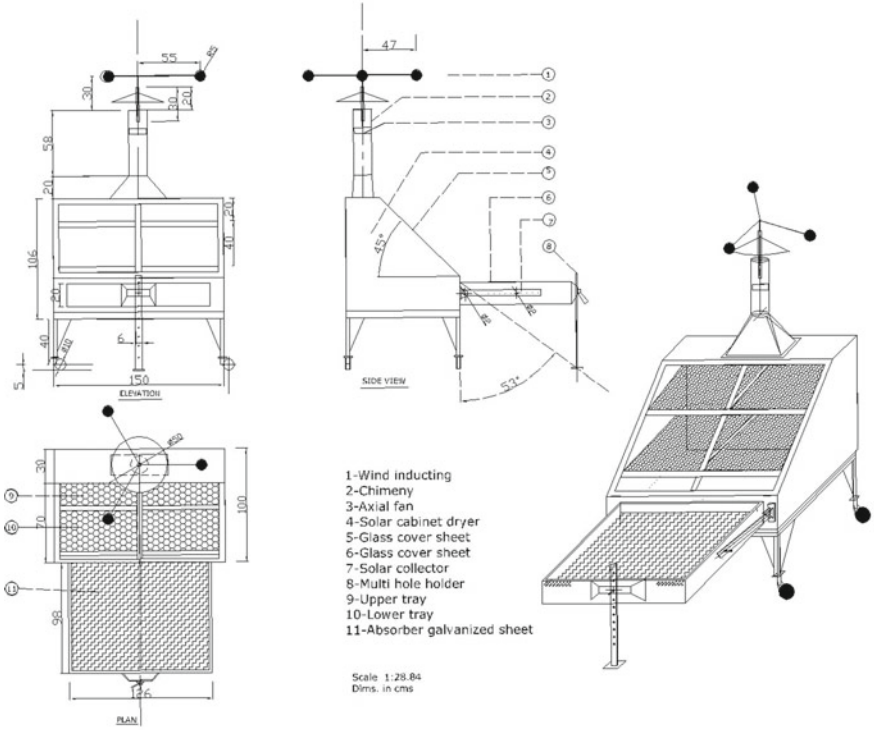


Fig. 9 Schematic diagram for the newly created solar-wind ventilation cabinet dryer (Eltawil et al. 2012)

held a vertical steel shaft with a 1 cm diameter on which the windmill was mounted. Three lightweight stainless steel cups with a diameter of 10 cm each made up the windmill and were fastened to the top of the steel shaft. These cups form a rotor with a diameter of 115 cm by rotating horizontally on a vertical pivot shaft. A metal lid with a 50 cm width in the shape of an inverted parabola covers the top of the chimney to keep dust and rainfall from entering the drying compartment. In order to reduce frictional resistance, ball, and footstep bearings were used. With the aid of a wind draft, the shaft of the suction fan is immediately rotated. Figure 9 shows the chimney's specifics in detail.

The bottom of the solar cabinet drying chamber is where the warm air from the solar collector is directed. When it hits the first tray, the crop absorbs its heat. The product on the second (higher) tray receives the air's sensible heat after which it is transferred before naturally exiting the cabinet at the top. Some of the sun energy that strikes the cabinet's front glazing enters the drying chamber and directly raises the temperature of the crop. During the dehydration process, the airflow rate can be increased by using a suction axial fan that relies on the natural wind for assistance. As a result, the dryer operates as a mixed mode type.

A full day of sunny, clear weather is needed for the product to dry, potentially less. Although it was done in batches, drying can also be done in a semi-continuous manner. Drying lasts from 9:00 am to 6:00 pm, or until the samples' weight loss almost ceases. Three weighed, labeled samples were weighed and placed in the middle of each tray to serve as a drying progress indicator.

According to the findings, the collector's tilt angle of 60° produced the maximum temperature for drying air, which was then followed by the dehydration system's tilt angle of 30°. The created solar collector dehydrator (SCD) proved capable of drying the chips and peppermint to a safe moisture level in around nine to ten and six hours (about one sunny day), respectively. With a 15-s fry time, the chips' best color was obtained. The panelists enjoyed the fried chips and dried peppermint. Superior quality for the dried goods is ensured by the SCD. The increased SCD is regarded as a viable method for drying potato chips and peppermint when taking into account elements like electricity requirement, frying time, health conscience, and exploitation of solar energy.

2.2 Greenhouse Technologies and Applications

Sunlight passes through the cover and strikes the opaque surfaces inside a greenhouse, which is an enclosed enclosure covered with materials like glass, fiber-reinforced plastic (FRP), and polyethylene film. This sunlight is then transformed into heat to some extent. Due to the heat trapped within the greenhouse, the air temperature increases, creating optimal conditions for plant growth (Syed and Hachem 2019). High production and efficiency arise from safeguarding the cultivated plants from severe outside conditions, pests, and diseases.

According to multiple factors, including size, orientation (east–west or south-north), coverage/shading and building materials, applications, and the technology employed to regulate the microclimate (methods either on-site or remote) (Ghani et al. 2019; Sahdev et al. 2019), Greenhouses can be classified into two categories: greenhouses for crop cultivation and greenhouses for crop drying. The purpose of crop-drying greenhouses is to produce dried crops of higher quality compared to the traditional method of drying under the sun. (Khanlari et al. 2020), Crop production greenhouses allow for year-round growing of vegetables, fruits, and flowers, even during the off-season (Yano and Cossu 2019).

In 2019, the United Nations' "Food and Agriculture Organization" (FAO) published the Early Warning Early Action (EWEA) report. The paper offers a thorough examination of the major dangers to the agricultural sector and global food security. According to this report, political unrest and climate-related calamities have a cumulatively harmful impact on food availability and production in several nations and areas. There is increasing evidence that climate change is presently affecting agriculture and food security, especially in nations with agricultural systems that are more susceptible to damage. Based on specific studies (Gorjian et al. 2020c; Veldhuizen et al. 2020), it has been found that the expansion of the agricultural sector is up to 3.2 times more efficient in reducing poverty compared to the growth of other sectors. The agricultural industry is also facing another important concern, which is the creation of "Sustainable Food Systems" (SFSs). These systems require a consistent energy supply to address the problem of unpredictable fuel expenses and improve food security (Nguyen 2018; Vadiee and Martin 2013). Agriculture's social, economic, and environmental goals, as well as those of other economic sectors, must all be recognized and balanced for agricultural and food systems to be sustainable (Compassion in World Agricultural 2008). All stages of the food chain rely on energy, including crop cultivation, forestry, dairy production, post-harvest applications, food storage, processing, transportation, and distribution. (Gorjian et al. 2020d).

Recently, renewable energy sources have shown significant potential for integration with traditional greenhouse designs. Solar energy can be considered a feasible option for integrating with agricultural greenhouses because it is a sustainable, expandable, and reliable renewable energy source that has no adverse environmental effects. By lowering the energy dependency of greenhouse agriculture systems on conventional resources in this way, the adoption of solar technology can help to reduce GHG emissions. Until recently, several academics have investigated certain solar technologies used in greenhouse buildings to perform studies on solar greenhouses.

2.2.1 Energy Consumption of Greenhouses

According to Acosta-Silva et al. (2019) and Golzar et al. (2018), the energy consumption in greenhouses can account for up to half of the production costs and be a factor in the second-highest operational costs. Heating, cooling, ventilation, fogging, appropriate shading, lighting mechanisms, and CO_2 enrichment systems are required to create the ideal growing conditions within the greenhouse (Hassanien et al. 2016).

All these pieces of equipment consume energy but heating and cooling applications demand about 65–85% of the supplied energy (Ahamed et al. 2019; Yano and Cossu 2019). Therefore, incorporating energy-saving technologies is a difficult task in greenhouse applications. The search for more dependable and sustainable alternative energy sources has been prompted by the drawbacks and high costs of fossil fuels (Mostefaoui and Amara, 2019). "In commercial greenhouses, the energy input is accounted for both directly and indirectly, and the energy output is equal to the product's energy value." According to Djevic and Dimitrijevic (2009) and Pahlavan et al. (2012), the Energy Ratio (ER), a measure of how efficiently energy is used in greenhouses, can be computed as follows:

$$ER = \frac{Energyoutput\left({}^{MJ}/_{m^2}\right)}{Totalgreenhouseenergyinputs\left({}^{MJ}/_{m^2}\right)} \quad (1)$$

The energy productivity (EP) can also be utilized for comparing the productivity of commercial greenhouses under various energy management scenarios in the following manner (Djevic and Dimitrijevic 2009; Pahlavan et al. 2012):

$$EP = \frac{Greenhouse\ Productivity\ yield\ \left(kg/m^2\right)}{Total\ greenhouse\ energy\ inputs\ \left(\mathrm{MJ/m^2}\right)} \tag{2}$$

Also, the Net Energy (NE) output can be used to compare the commercial greenhouses as follows (Djevic and Dimitrijevic 2009):

$$\begin{aligned}\text{Net Energy (NE) output} = {} & \text{Total greenhouse energy output } (\mathrm{MJ/m^2}) \\ & - \text{Total greenhouse energy input } (MJ/m^2)\end{aligned} \tag{3}$$

2.2.2 Solar Greenhouses Technologies

Solar energy is now a competitive substitute for carbon-based conventional fuels thanks to several impressive breakthroughs in solar technology (Loni et al. 2020; Mirzamohammadi et al. 2020). Solar thermal and PV technologies are the two primary categories of solar energy technology. In solar thermal technology, flat-plate and concentrating solar collectors convert solar radiation's energy into heat, which can then be stored for use in a variety of domestic, residential, and commercial applications (Mekhilef et al. 2011). PV systems can convert sunlight directly into electricity because they use semiconductors.

Thermal and PV applications in agriculture both aim to increase profitability in this sector through enhanced yields, decreased losses, quicker production, and better resource management (Mohsenipour et al. 2020). Passive greenhouses and active greenhouses are the two types of solar-powered agricultural greenhouses.

By integrating solar systems like PV, PVT, or solar thermal collectors, active solar greenhouses (ASGs) are intended to increase the absorption of solar energy. In contrast, passive solar greenhouses (PSGs) seek to enhance solar energy absorption (Gorjian et al. 2020d). Using thermal energy storage (TES), the overall thermal performance of the greenhouse may be increased in either design.

Compared to active solar greenhouses, PSGs feature more straightforward architecture. Conversely, according to Shukla et al. (2016), active solar greenhouses have reduced capital and operating costs. Active greenhouses do, however, have better thermal performance, which can help offset some of the expenditures and boost their profitability.

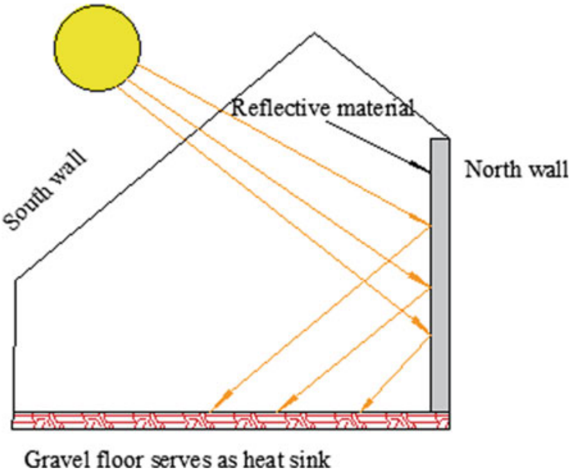


Fig. 10 Schematic view of a typical passive solar greenhouse (PSG) (Solar Greenhouses 2020)

2.2.3 Passive Solar Greenhouses (PSGs)

Li et al. (2018) claim that depending on where the sun is in the sky, different amounts of solar radiation are absorbed by the greenhouse in PSGs. The length of the south-facing wall is extended along the east–west axis, as shown in Fig. 10, to maximize the amount of wall area that is exposed to the sun.

To prevent heat loss and produce shadows inside the greenhouse, the east and west-facing walls' areas have been lowered (Çokay et al. 2018). PSGs frequently include thermal collecting elements, allowing the greenhouse to absorb solar radiation during the day and send any surplus heat to heat-storage materials including water, rock bed, soil, and phase change materials (PCMs), so maximizing the solar gains. According to Gorjian et al. (2021), the water heat storage units-which frequently resemble water-filled plastic bags-are placed either outside or indoors on the ground between rows of crops and along the north side of greenhouses. A PSG's overall effectiveness is influenced by a number of variables, including the size of the greenhouse, the materials used for the cover, the type of cultivation, and the location of the greenhouse's installation.

2.2.4 The Greenhouse Integrated PV

An emerging technique that helps greenhouses lessen their dependency on fossil fuels is the usage of PV systems. Similar to how they are connected to buildings, solar PV modules can be attached to greenhouses, but this requires different techniques because sunlight must enter the greenhouse through transparent cladding (Allardyce et al. 2017). Furthermore, a consistent and dependable energy source is needed for greenhouses. Distributed energy resources (DER) like solar and wind power systems would be suitable alternatives as a result (Callejon-Ferre et al. 2011).

The two main types of solar PV systems connected to agricultural greenhouses are on-grid and off-grid systems. The electricity generated by the PV modules in on-grid PV systems is used directly by the greenhouse, with any extra energy being fed into the power grid (Fig. 11a). Off-grid methods can be utilized to generate electricity when utility power isn't accessible (Gorjian and Shukla 2020). This kind of PV system often uses a backup battery bank in addition to a fossil-fueled generator (Fig. 11b). In greenhouses, grid-connected photovoltaic (PV) systems are the most commonly used. However, integrating with off-grid systems is the optimal choice for installing in areas where the electric grid is inaccessible due to long distances or challenging topography (Eltawil and Zhao 2010; Perez-Alonso et al. 2012).

2.2.5 Greenhouse Integrated PV Thermal

The Greenhouse Integrated PVT (GHIPVT) Solar PV modules are capable of converting sunlight into energy with an efficiency of 15% to 18%. The quantity of solar energy wasted as heat as a result of this process, however, significantly reduces power generation and raises the surface temperature of the PV module (Debbarma et al. 2017; Shakouri et al. 2020). Being both an electrical generator and a thermal collector has advantages for a hybrid PVT module. By removing excess heat from the PV module through the use of the cooling medium, which is frequently air or water, this hybrid collector boosts overall electric efficiency. The extracted heat can then be used for low- to medium-temperature applications (Gorjian et al. 2020b). Figure 12 gives an overview of PVT modules.

Concentrating PVT (CPVT) modules use curved reflectors or refractors (Fig. 13) to direct solar energy onto the multijunction (MJ) or non-silicon solar cells, with potential efficiencies approaching more than 40%. The exceptional optical and thermal efficiencies of CPVT modules make them among the most effective hybrid collectors (Daneshazarian et al. 2018).

2.2.6 Greenhouse-Integrated Solar Thermal Collectors

Solar thermal applications have attracted considerable attention due to their remarkable energy conversion efficiency and energy storage density. Solar collectors and thermal energy storage units are the two primary parts of solar thermal systems (Ketabchi et al. 2019). Thermal collectors are utilized in greenhouse applications to absorb solar radiation and generate heat, which can then be transferred to the interior of the greenhouse. This provides an optimal thermal environment for the plants cultivated within. (Gorjian et al. 2020a). Additionally, the generated thermal energy may be saved in an energy storage system for usage at night or on overcast days. According to Sethi and Sharma (2008), there are two basic types of solar thermal collectors: non-concentrating and concentrating varieties. Figure 14 depicts a categorization of non-concentrating solar thermal collectors.

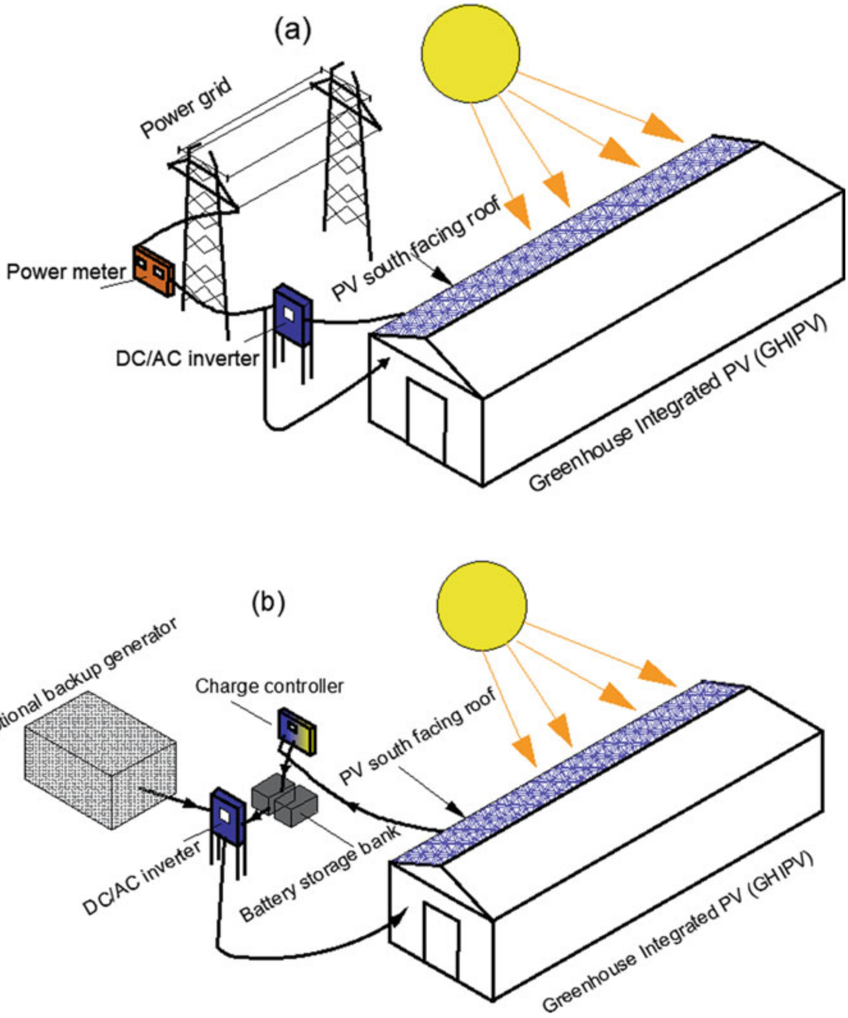


Fig. 11 Typical configurations of a GHIPV system; **a** on-grid GHIPV system, **b** off-grid GHIPV system with a backup generator and batteries

2.2.7 Solar Greenhouses with Thermal Energy Storage Integrated

Thermal Energy Storage (TES) devices enhance the performance of solar-powered greenhouses, according to Kant and colleagues (2016b, 2017). These systems accomplish this by storing the extra heat generated during daytime operations, then using the energy throughout the night and on overcast days. For this reason, some individuals believe that a capable and reasonably priced TES is a crucial component of solar greenhouses. Sensible, latent, and chemical energy storage are the three fundamental ways to store heat, according to Hosseini et al. (2018). A list of the fundamental TES

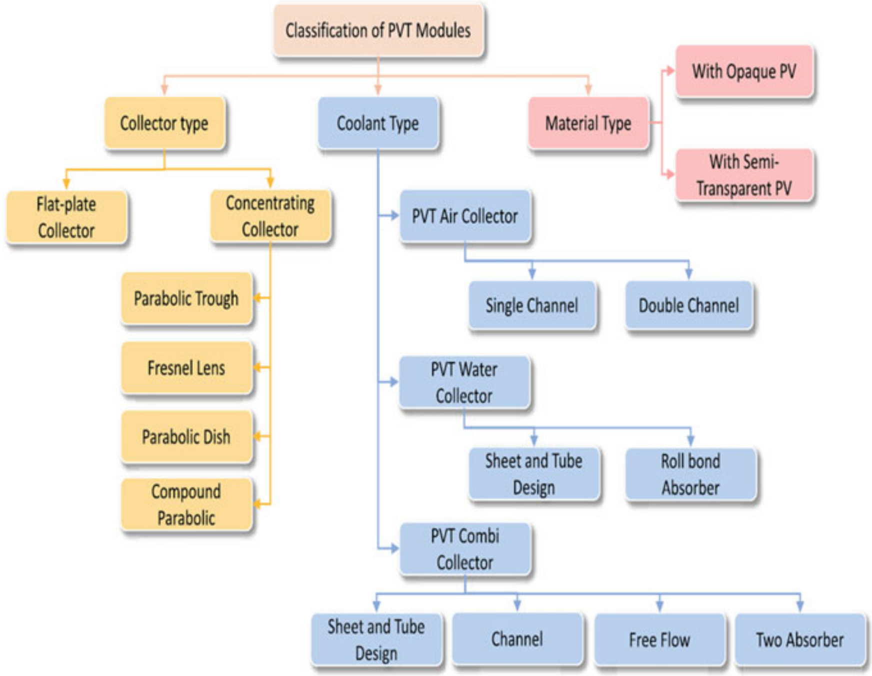


Fig. 12 Classification of solar PVT modules, from (Diwania et al. 2019)

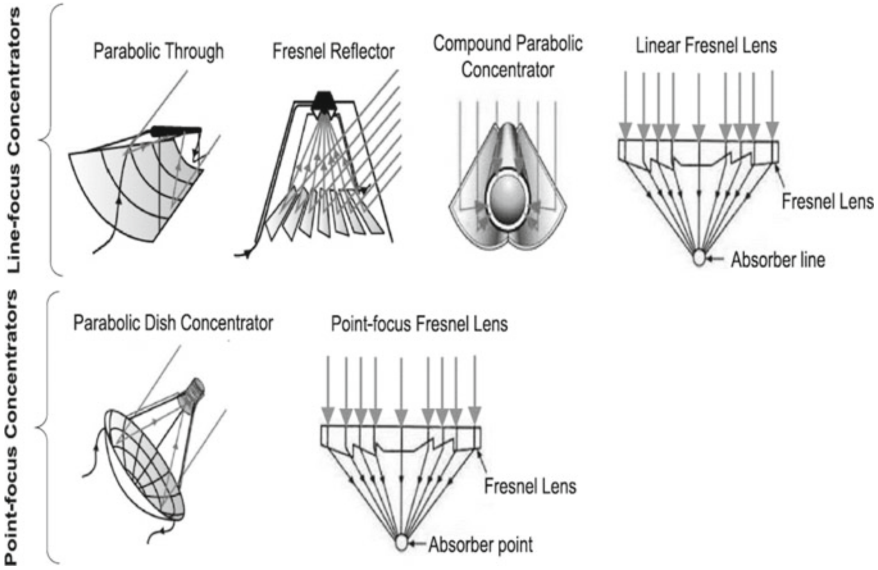


Fig. 13 Different types of solar concentrators which are used in CPVT modules (Gorjian et al. 2021)

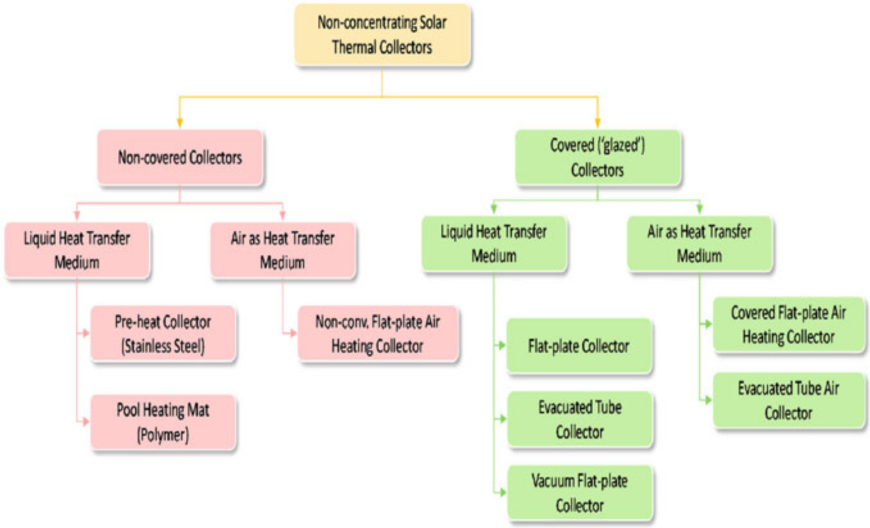


Fig. 14 Classification of non-concentrating solar thermal collectors (Fortuin and Stryi-Hipp, 2012)

methods is shown in Fig. 15. Solar flat plate collectors (FPCs) were used by Bargach et al. (1999) to create a heating system that enhanced the environment within a greenhouse (Fig. 16).

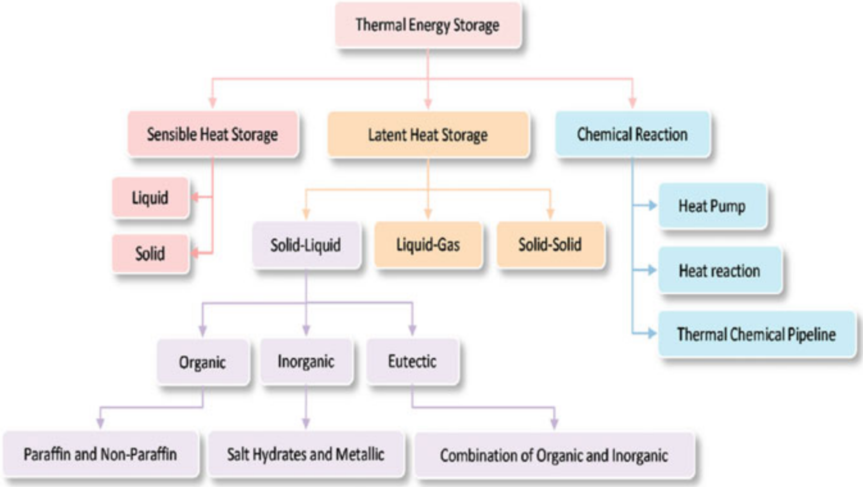


Fig. 15 TES system classification, modified from Sharma et al. (2009a, b)

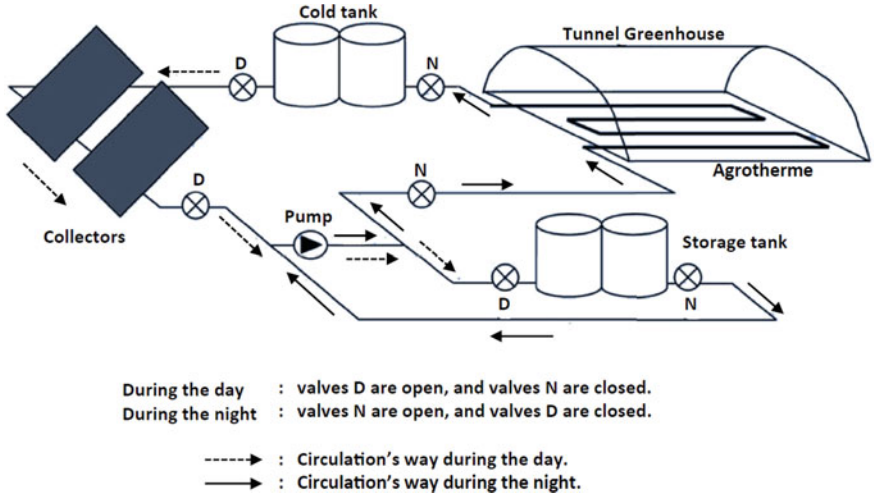


Fig. 16 The greenhouse tunnel equipped with a solar flat plate collectors (FPCs) heating (Bargach et al. 1999)

2.2.8 Greenhouse Cooling

The recognition of the global energy crisis has led scientists and engineers to focus on harnessing alternative energy sources. Solar energy is one such promising source, and efforts are being made to utilize it for domestic, agricultural, and industrial purposes.

Due to its many advantages, solar photovoltaic (SPV) technology has a huge potential for capturing solar energy. These benefits include simple and environmentally beneficial solar cell electricity generation. In order to reduce carbon dioxide (CO_2) emissions and give off-grid rural populations access to high-quality electricity, SPV must be developed and widely used. However, it is important to considerably lower the cost of SPV electricity in order to reach broad use.

In tropical and subtropical locations or in places with difficult climatic conditions, a greenhouse is an effective method for sustaining food output. When it's hot outside, a greenhouse's internal temperature rises and goes above optimal levels as a result of the heat that enters the structure.

The crops, soil, and greenhouse construction elements (shown in Fig. 17) absorb the solar radiation that enters the greenhouse. Subsequently, these warm objects release the energy back outwards. The extent of heat loss through radiation depends on the glazing material used, the surrounding temperature, the cooling/heating systems employed, and the level of cloud cover present.

The exchange of energy between a greenhouse, which contains a crop, and its surroundings can be achieved through various cooling systems. These systems include ventilation shading and evaporative cooling. Evaporative cooling, in particular, is commonly used in greenhouses due to its simplicity and controllability. There

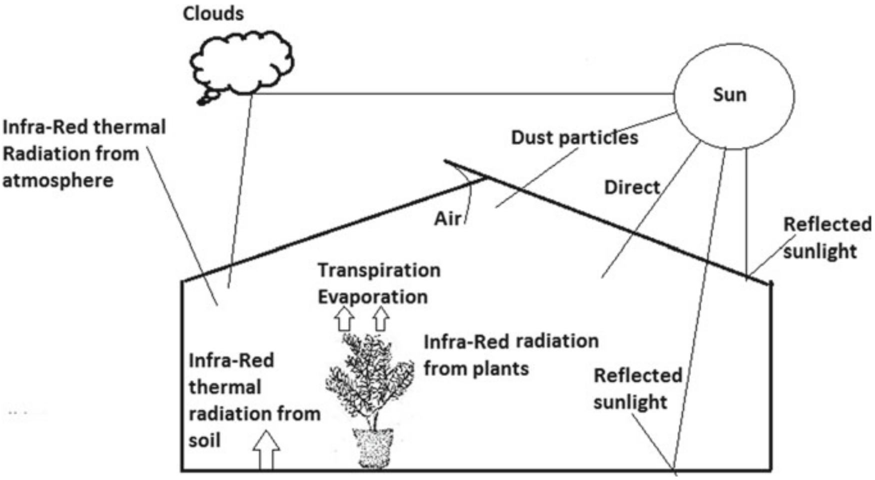
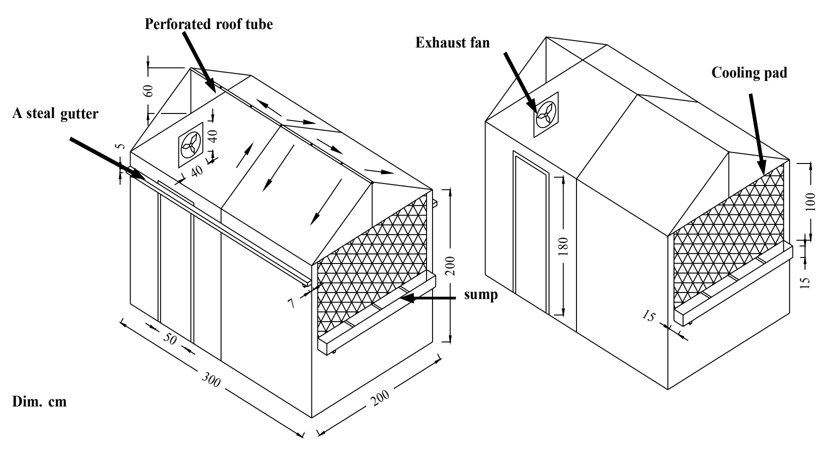


Fig. 17 Energy transfer between the environment and a greenhouse with a crop produced inside

are several methods of evaporative cooling currently utilized, including fogging, the fan-pad method, and misting. These methods work by increasing heat and mass transfer rates by using fans to force air movement across a larger surface area of liquid water, promoting evaporation. The porous pad used in the fan-pad method can be wetted either by water flow or by dripping water onto its upper edge. However, commercially available pad cooling materials tend to be complex, expensive, and not easily accessible. As a result, it becomes necessary to investigate and assess the suitability of locally available materials in agricultural areas for use as alternative cooling pads. Various researchers have studied the feasibility of such alternative cooling pads for greenhouse use.

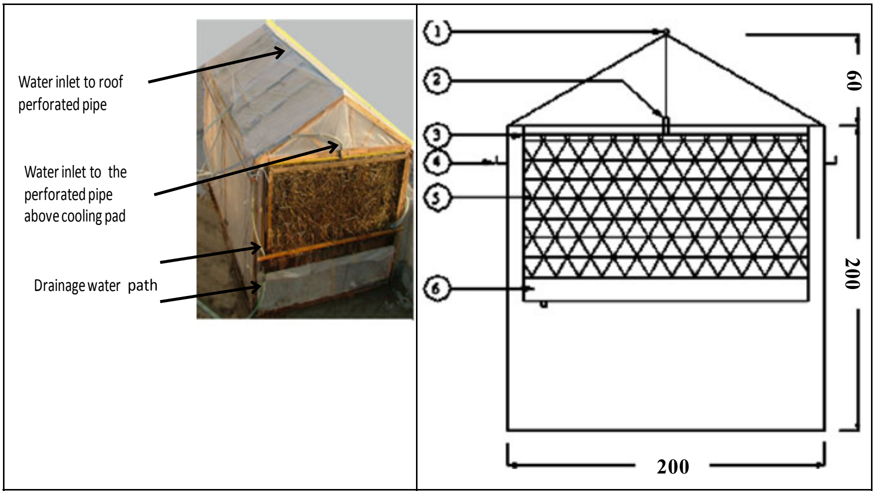
Helmy et al. (2013) built a greenhouse with an evaporative cooling system to minimize the effects of heat stress. They designed and installed two small-scale greenhouses on the roof of a house. Both greenhouses utilized a fan-pad system for cooling. However, they experimented with a hybrid system in one of the greenhouses by applying a thin water film on the roof between two layers of polyethylene cover and fan-pad. This setup aimed to analyze the impact of the roof water film on the cooling effectiveness, as shown in Figs. 18 and 19. The identical circumstances were used to compare the two cooling systems. *Cyperus alopecuroides* Rottb (Samar), *Cyerus alternifolius* (Purdy), and *Cyperus Rotundus* l (Nut-grass or Se'd) were three new materials for evaporative cooling pads that were gathered from the field, modified, and tested. The different characteristics of the newly adapted cooling pad materials are given as follows: Cyperus Rotundus l (Nut-grass or Se'd) is available in the agricultural field, triangle in shape, and hollow structure. Cyerus Alternifolius (Purdy) is available in ditches, channels, and drainage; semi-circle in shape, and spongy structure. Cryperus Alopecuroides Rottb (Samar) in the agricultural field, triangle in shape, and solid structure.



(A)) Roof water flow system with fan-pad system

(B) Fan-pad system.

Fig. 18 The two experimental greenhouses that will be cooled are shown in a schematic diagram (Helmy et al. 2013)



System that combines a hybrid roof water flow with a fan-pad and uses Se'd as an evaporative cooling substance.

1. Perforated pipe on top, 2. Water control valve, 3. Perforated pipe, 4. Gutter, 5. Cooling pad, 6. Sump).

Fig. 19 Picture and schematic diagram of hybrid cooling systems arrangement (dimensions in cm) (Helmy et al. 2013)

To examine the cooling performance, two different thicknesses of 10 and 15 cm were used, with air velocities on the pad faces ranging from 0.45 to 1.01 m/s. Each greenhouse had a vertical evaporative cooling pad attached to it. The second greenhouse combined roof water flow and a fan-pad system, whereas the first one ran on a fan-pad system.

The researchers measured and recorded the dry and wet bulb temperatures at nine locations within each greenhouse. They also measured the energy consumption of the cooling system under various operating conditions. Additionally, they recorded the environmental parameters outside the greenhouse, including outside solar radiation, dry bulb temperature, wet-bulb temperature, and relative humidity.

The greenhouse cooling efficiency can be calculated as follows (Koca et al. 1991):

$$\eta_{\text{cool}} = \frac{(T_o - T_i)}{T_o - T_{owb}} \times 100 \tag{4}$$

where:

η_{cool} = the greenhouse cooling efficiency, %

T_i and T_o = the dry temperatures of air inside and outside the greenhouse, °C, respectively, and T_{owb} = wet bulb temperature of outside air, °C."

According to the findings, the suggested cooling pads in the evaporative cooling systems might keep greenhouse model microclimates at a tolerable range. Particularly, it was discovered that the Se'd pad material reduced temperature more successfully. The temperature within the greenhouse was found to be lower than that of a fan-pad greenhouse in the morning and afternoon by about 1.1–5.44 °C, respectively, when operated using a combination of roof water flow and a fan-pad system. The air relative humidity increased due to the cooling system, which prevented excessive transpiration and crop damage. The Se'd, Purdy, and Samar pad materials were able to attain daily average cooling efficiencies of 88.4, 83.1, and 79.6% over testing days in the hybrid system at a 15 cm pad thickness and 0.45 m/s pad face air velocity. In comparison to other materials, the Se'd pad material showed the maximum efficiency and might be used as an alternative.

2.3 *Solar Refrigeration Applications*

Solar cooling can play an important role in the handling and usage of agricultural products, such as crop storage. (Eltawil and Samuel 2007a, b; Eltawil et al. 2023), medicine storage, and vaccine or drug preservation (Abdul-Wahab et al. 2009), ice making, and air conditioning.

Solar cooling can be classified into two primary methods: PV-powered cooling systems (Eltawil and Samuel 2007a, b; Eltawil et al. 2023; Saidur et al. 2008), and adsorption, desiccant, and absorption (Kalkan et al. 2012). Figure 20 shows different cooling cycles incorporated with PV systems.

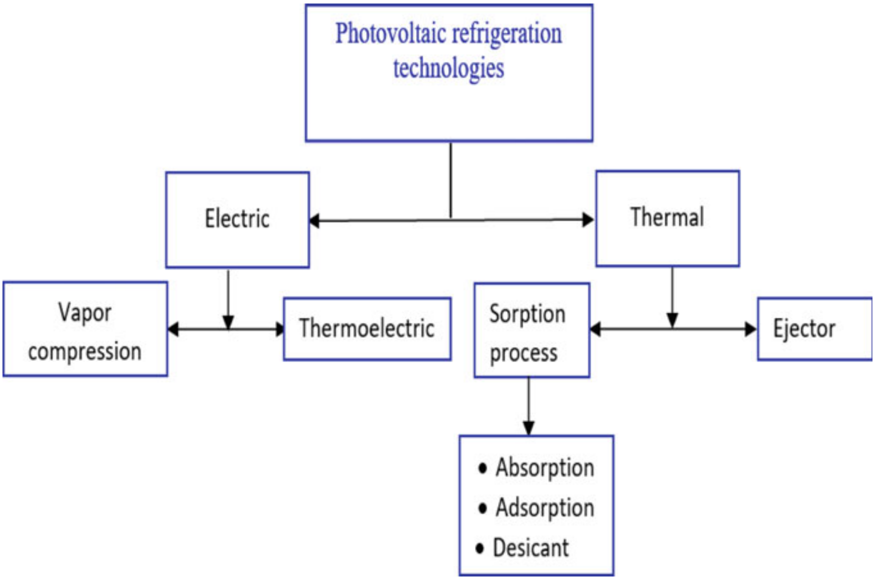


Fig. 20 Different cooling cycles incorporated with PV systems (Alsagri 2022)

The foregoing section showed the main cooling cycles, so solar cooling based on these processes has been pointed out.

2.3.1 Absorption Refrigeration

Because the solar absorption cooling cycle is classified as solar thermal refrigeration cycles, to supply the thermal energy needed for refrigeration, solar collectors, photovoltaic thermal collectors (PVT), and concentrating photovoltaic thermal collectors (CPVT) must be used (Maidment et al. 1999; Zhai et al. 2011). As pointed out in the literature absorption cooling was applied for vaccine storage. According to Siddiqui and Said (2015), the PVT is used in hybrid absorption processes such compression absorption refrigeration and ejector-absorption systems as well as absorption cooling cycles.

2.3.2 Adsorption Refrigeration

The process of adsorption, when using the right adsorbents, is comparable to that of absorption (Sah et al. 2015). Metal–organic frameworks (MOF) were examined by Rafique (2020) as promising adsorbents for solar cooling applications and it was discovered that the MOF might enhance the cooling cycle's efficiency. But the reduced COP makes this method less workable. Therefore, this system can be used for air conditioning and ice maker facilities as mentioned by (Dieng and Wang 2001).

2.3.3 Desiccant and Ejector Refrigeration

An experimental investigation on the dehumidifier and regenerator of a liquid desiccant cooling air conditioning system was carried out by Yin et al. in 2007. They emphasized that air conditioning is the primary use for desiccant cooling. Concerning thermal energy, ejector refrigeration is considered a low-grade technology, but because of its simplicity, the usage of this technology has become applicable. Several research works investigated the integration of ejectors with compression or absorption cycles (Braimakis 2021; Chen et al. 2013).

2.3.4 Vapor-Compression Refrigeration

One of the appliances that uses a substantial quantity of electricity is a refrigerator. Therefore, in order to lower greenhouse gas emissions and the price of PV systems, a decrease in energy consumption and efficient systems are crucial (Ekren et al. 2011; Mohammed et al. 2022).

PV systems as an alternative source of energy can be used to operate vapor-compression refrigeration. This application can be used for preserving vaccines, domestic refrigerators, icemakers, and cold storage. The combination of compression refrigeration with PV systems showed better economic potential compared to other solar refrigeration options (Ferreira and Kim 2014). In their review, they specifically examined thermodynamic and economic studies. Therefore, the significance of utilizing vapor compression refrigeration powered by PV can be seen.

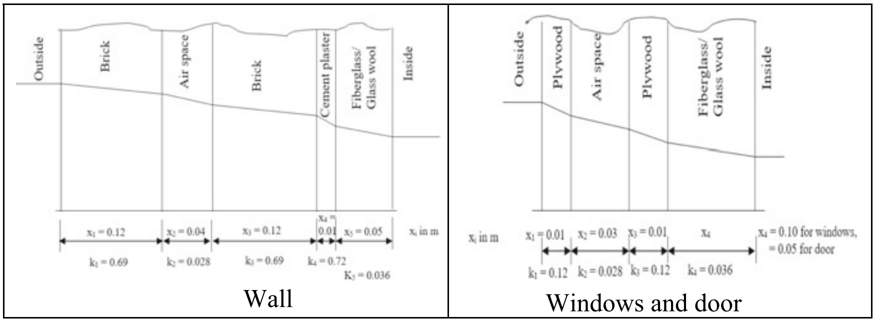
Refrigeration in remote areas that away from the electricity grid need an off-grid power system. Solar energy (Photovoltaic) is considered an important power source for operating off-grid refrigeration. Recently, due to a reduction in PV system cost, therefore, solar-powered refrigerators have become more economical (Ayadi and Al-Dahidi 2019; Gao et al. 2018). During day time, the refrigeration system can be operated on PV modules but, the batteries are required to store extra energy during the daytime for usage at night (Li and Uckun 2016).

2.3.5 Solar PV-Powered Vapor Compression Refrigeration for Potato Storage

In order to create the ideal conditions for preserving potatoes, Eltawil and Samuel (2007a, b) conceived and constructed a solar PV-powered cooling system that use vapor compression refrigeration. The system had 490 W worth of PV panels, a lead-acid battery, and an inverter. Along with its primary parts, the vapor compression refrigeration system had a drier-cum-filter, an AC compressor, a condenser, an expansion device, an evaporator, an exhaust device, and evaporator fans. A cold storage structure with a capacity of 2.50 m^3 was built outside and properly insulated. Additionally, a storage structure with a capacity of 1.0 cubic meter, cooled by evaporation, was used for curing potato tubers. Figures 21, 22, 23, 24, 25 and 26 show the structural details of the constructed PV-powered cold store. The Kufri Chandermukhi variety of dried potatoes was kept in storage for five months. The performance of the designed system was evaluated. The potatoes' shelf life and the economics of the system were evaluated under different operating conditions. The potato tubers that had been stored were separated into two groups. The first group was used as a control and was allowed to sprout freely, while the second group underwent manual desprouting. The shelf life of the potato was determined by measuring the loss of moisture, dry matter, sprouting, rotting, sugar content, starch, and the quality of chipping.

The specifications of the vapor compression cooling system used in the experimental work are given in Table 2

The obtained results can be summarized as follows:



Wall

Windows and door

Fig. 21 Construction of the cold store's walls, windows, and door (Eltawil and Samuel 2007a)

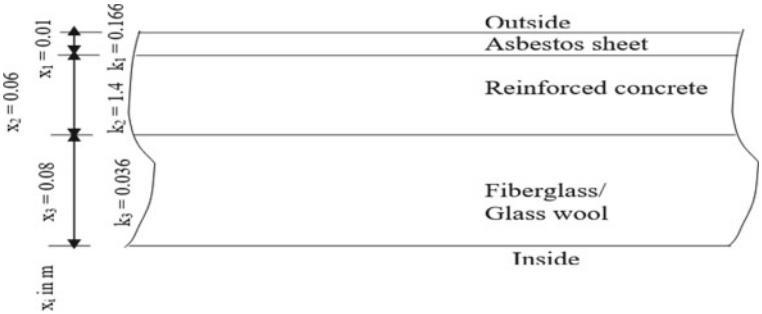


Fig. 22 Construction of ceiling (roof) (Eltawil and Samuel 2007a)

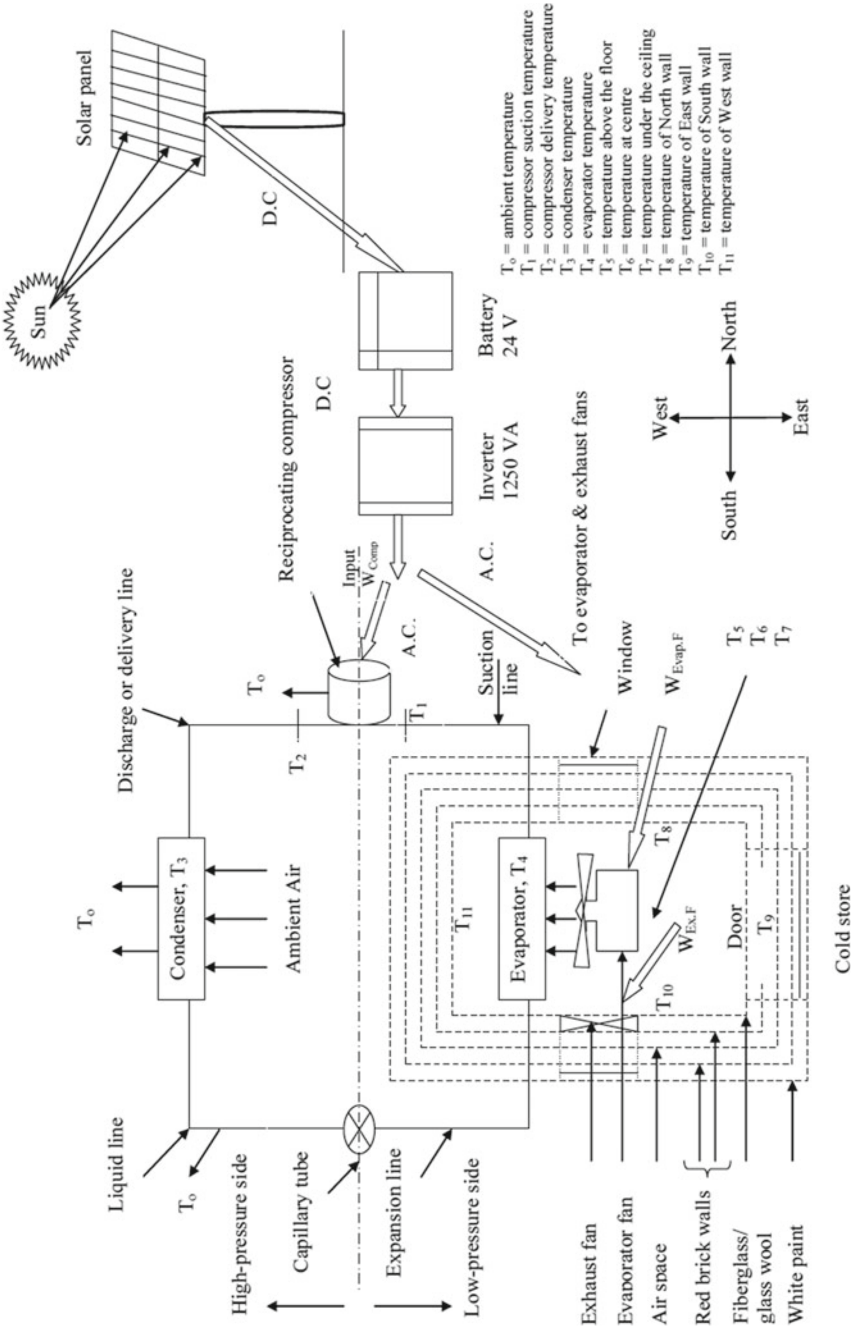


Fig. 23 Vapor compression cooling system for cold storage, schematic diagram driven by solar PV (Eltawil and Samuel 2007a)

Fig.24 Solar photovoltaic powered cold store (Eltawil and Samuel 2007b)

Fig.25 Curing of potato tubers using evaporatively cooled rice straw pad structure (Eltawil and Samuel 2007a)

- The average daily PV efficiency was about 11.73%, while the PV power output was 84.91 W.
- The average daily conversion efficiencies of PV modules were recorded as 8.90%, 7.77%, and 10.74% for module temperatures of 317.7 K, 318.3 K, and 299.1 K, respectively. These measurements were taken on clear sunny days during the summers of 2001 and 2002, and the winter of 2002.
- In order to charge the battery and run the cooling system over night, the solar panel supplied 490W of power. It was discovered that the energy supply from the panels decreased by 33.6% when the system was under full load. Additionally, it was determined that the output power was, on average, 26.53% higher than what the cooling system required when operating at full load.

Fig. 26 Inside view of cold store structure without load and loaded with cured potato tubers (Eltawil 2012)

Table 2 Specifications of vapor compression cooling system

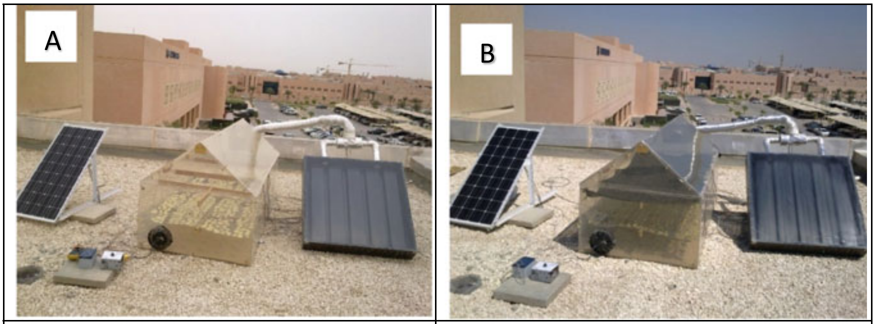
Item	Specifications
Drier	Silica gel
Compressor	• Reciprocating sealed compressor, model number AE7 ZA7, 230 V, 1.4 A, 50 Hz, IP-LRA-9-R12 • 33.096 kN/m^2 is the suction pressure, while 1241.1 kN/m^2 is the discharge pressure
Condenser	• 24 tubes (18 main tubes + 6 secondary tubes), 17.90 m length, 0.3374 m^2 area • Fixed at 0.10 m behind the West wall (windward direction), ambient air is used for cooling the condenser
Evaporator	• 6 copper tubes of 1.0 cm dia, 0.2230 m^2 area, 7.10 m length
Chiller	• A chiller (tray) was kept under the evaporator to collect the condensed moisture from the air
Refrigerant	• A refrigerant of Freon-12 (250 ml) was utilized to serve at different operating temperatures
Expansion device	A 3.0 mm diameter capillary tube of 2.0 m length was connected to the evaporator exit tube in order to sub-cool the condensate
Thermostat	For controlling temperature, a mechanical type thermostat was used

- The cooling system, when operating at full capacity with stored goods and air-circulated cold storage, produced an average daily SPV power output of 5.60 kWh/d and had an energy consumption of 4.115 kWh/d.
- During the testing sunny days, the loaded and air-circulated cold storage structure's coefficient of performance (COP) varied from 2.83 to 3.62, with an average daily COP of 3.25.
- Taking into account various losses, the overall efficiency of the entire system was about 5.97%.
- For the conditions of empty and non-air circulated, empty and air circulated, and loaded and air circulated, respectively, the average temperatures inside the storage structures during the experiment were recorded as 285.39, 280.94, and 283.13 K, along with the corresponding inside relative humidities of 73.94, 81.21, and 86 percent.
- The overall expense of preserving and storing 1.0 kg of potatoes in a 2.5 cubic meter cold storage facility powered by a subsidized photovoltaic system, taking into account the 6% reduction in potato weight, is estimated to be 9.02 Rupees (1 US dollar = 46 Rupees). Conversely, if the system were operated using grid electricity (at 3.5 Rupees per kilowatt-hour) or a petrol-kerosene generator (at 10.47 Rupees per kilowatt-hour), the total costs per kilogram of potatoes would amount to 7.66 and 14.63 Rupees, respectively.
- The power output and temperature of the PV panel can be predicted using a number of multiple regression equations that have been developed. These equations can also forecast how much energy the cooling system would need and how well it will work.

3 Case Study in Saudi Arabia

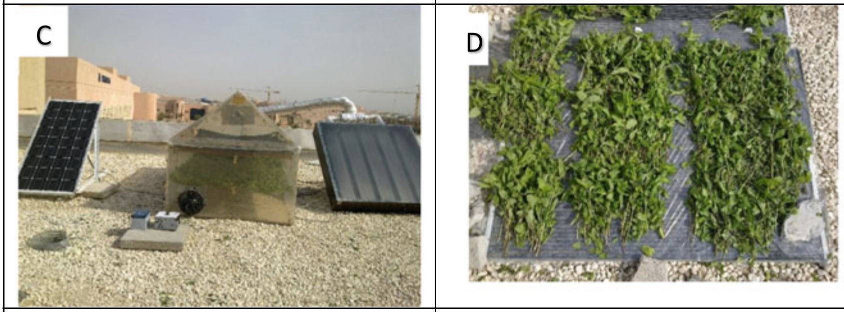
3.1 Developed Solar Drying

Eltawil et al. (2018a, b) conducted a study on a solar tunnel drier (STD) that utilized a solar PV system to dry potato chips and peppermint. Figures 27 and 28 illustrate that the STD comprises a flat plate solar air collector and an axial DC fan, which were implemented to enhance thermal efficiency and maintain the drying chamber at an elevated temperature. The performance of the STD was assessed with and without a load, as well as with and without a thermal curtain placed on top of potato slices on sunny days. They investigated different levels of airflow rates (2.1, 3.12, and 4.18 m^3/min) and pre-treatments for potato slices. With an airflow velocity of 3.12 m3/min, the PV-powered STD was able to produce chips with a safe moisture level in 6 and 7 h, respectively, without and with the use of a thermal curtain. The frying time for potato chips was reduced to only 15 s. Using a black thermal curtain placed above the slices, 1% sodium meta-bisulfite produced the best chips in terms of color. Several thin-layer drying models were used to compare the predicted and



Mixed mode without shade on the potato slices

Mixed mode with shade on the potato slices



Mixed mode without shade on the peppermint

Open sun drying for peppermint

Fig. 27 The experimental setup involves a solar photovoltaic (PV) powered tunnel dryer designed for potato chips and peppermint. Two scenarios were tested: drying without shading and drying with a black thermal curtain on the product (Eltawil et al. 2018a, b)

experimental moisture ratios of chips using the developed STD. At an airflow of 0.0786 kg/s, the maximum drying efficiencies of 28.49 and 34.29% were achieved when a thermal curtain was not used.

Eltawil et al. (2018b) investigated a hybrid portable solar tunnel drier for drying peppermint using a flat plate solar collector and solar photovoltaic system, as shown in Figs. 28 and 29. The solar tunnel dryer can function in both direct and indirect thermal heating modes. A DC fan powered by the solar system runs in forced mode. A thermal curtain is also included to shade the mint and protect it from the sun's rays. The efficiency of the solar tunnel dryer was compared with open-air sun drying using one, two, or three layers of mint. Predicted and experimental moisture ratios of mint leaves dried in the solar tunnel drier were compared using several thin-layer drying models. The energy and environmental impacts of the hybrid solar tunnel dryer were also studied. The results indicated that the solar tunnel dryer took between 210 and 360 min to dry peppermint, whereas open-air sun drying took between 270 and 420 min. Among the models tested, the two-term model proved to be the most effective in simulating the thin-layer drying process of peppermint. The dryer efficiency, daily average photovoltaic efficiency, and total efficiency were 30.71%,

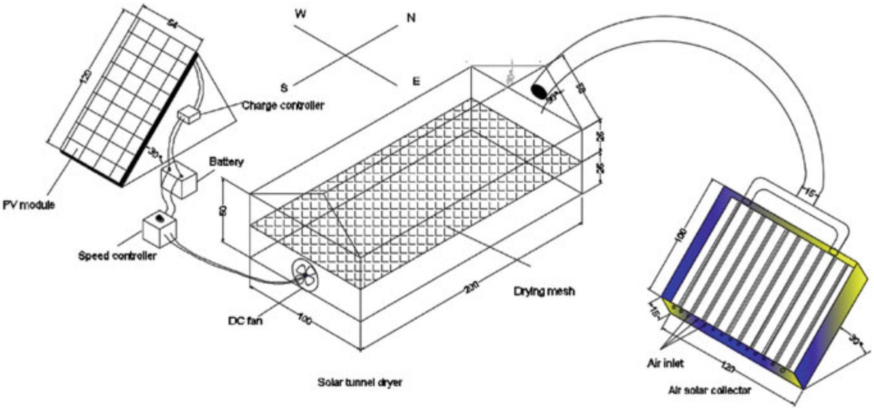


Fig. 28 The complete experimental setup's schematic diagram (Eltawil et al. 2018b)

9.38%, and 16.32%, respectively. The energy payback time was 2.06 years, and the lifetime net carbon dioxide (CO_2) mitigation was 31.80 tons. Peppermint dried in the solar tunnel dryer with a black thermal screen has better quality than peppermint dried in direct sunlight because it maintains its natural color and appearance. This technology is suitable for farmers and individuals living in distant locations without grid access. According to Eltawil et al. (2018b), drying peppermint using a black thermal curtain in a sun tunnel drier results in a higher standard of drying compared to drying it outside.

Azam et al. (2020) sought to create a standalone hybrid solar greenhouse dryer (GD) for small-scale tomato postharvest processors that incorporates a PV system and solar collector. To evaluate the thermal performance of the GD, which employs forced convection mixed-mode drying, the researchers used a mathematical model.

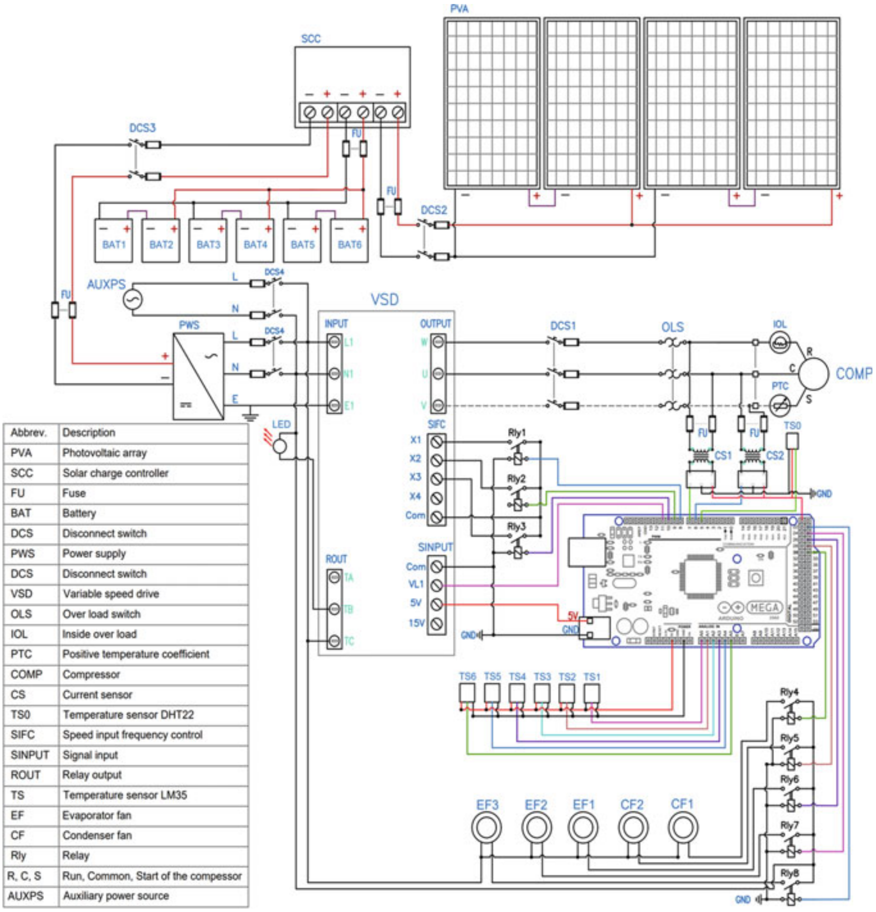
Fig. 29 Experimental setup of a solar PV-powered greenhouse dryer for drying tomatoes (Azam et al. 2020)

In order to find the best pretreatment and compare the final product's quality to open-air drying, they looked at a variety of pretreatments on fresh tomatoes, including full, half, and sliced, with and without blanching, and with and without sugar. The findings showed that compared to treatments without blanching, drying tomatoes in hot water for 15 min prior to drying resulted in a higher initial drying rate. According to the thermal energy analysis, the hybrid GD could capture useable heat gain from 6.45 to 26.62% of the solar energy that was available. The average daily heat gain dropped from 60 to 5% during the drying process. It was discovered that the hybrid GD's average total efficiency may reach 17.96% (refer to Fig. 29 for more details). Lastly, the technology is suitable for farmers without grid access, as it preserves the natural aspect and hue of the sun under shadowing.

3.2 Solar Display Refrigerator

Eltawil et al. (2023) developed and assessed an intelligent control system (ICS) for solar-powered display refrigerators (SPDRs) using machine learning and artificial neural networks (ANN). Figure 30 demonstrates the block diagram employed in the solar display refrigerator. while Fig. 31 shows the different components of the experimental setup. The refrigerator components and their specifications are summarized in Table 3. The SPDR was first run at a constant 60 Hz frequency. The proposed ICS combined with a variable speed drive based on ANN technology was then used to operate it at varied frequencies between 40 and 60 Hz. The necessary energy was provided by a standalone PV system. The performance of the developed SPDR was assessed and compared to its performance under a traditional control system (TCS) when operated at refrigeration temperatures of 1, 3, and 5 °C, which correspond to ambient temperatures of 23, 29, and 35 °C.

Figure 32 compares the SPDR with a modified ANN-based control system (MR) and the SPDR with a traditional control system (TR) in terms of their average daily power usage at a daily average temperature of around 29 °C and a product temperature of 3 °C. The Figure makes it clear that the MR uses less electricity than the TR and works the refrigeration system extremely smoothly. At average ambient temperatures of 23 °C, 29 °C, and 35 °C, respectively, the MR saved about 32.9, 33.4, and 35.5% more power when aiming for a product temperature of 5 °C than the TR. The solar PV system enables the operation of refrigerators in rural areas without relying on the electricity grid. The MR is expected to serve as the foundation for designing and optimizing PV-powered refrigeration systems. The results indicate that the power-modified control system (MCS) enhances the energy consumption and coefficient of performance (COP) of the SPDR. The ANN-based regression model is a more efficient and reliable control method that can be implemented in other refrigeration systems. To assess the effect of this improved solar-powered display refrigerator with the created ANN control system on the preservation of chilled fruits and vegetables, additional research is required.



Abbrev.	Description
PVA	Photovoltaic array
SCC	Solar charge controller
FU	Fuse
BAT	Battery
DCS	Disconnect switch
PWS	Power supply
DCS	Disconnect switch
VSD	Variable speed drive
OLS	Over load switch
IOL	Inside over load
PTC	Positive temperature coefficient
COMP	Compressor
CS	Current sensor
TS0	Temperature sensor DHT22
SIFC	Speed input frequency control
SINPUT	Signal input
ROUT	Relay output
TS	Temperature sensor LM35
EF	Evaporator fan
CF	Condenser fan
Rly	Relay
R, C, S	Run, Common, Start of the compressor
AUXPS	Auxiliary power source

Fig. 30 The solar-powered display refrigerator's block diagram (Eltawil et al. 2023)

3.3 Date Fruits Syrup (Dibs) Extraction Using Electro-Thermal Solar Energy

Dates are an important crop in the Kingdom of Saudi Arabia due to their high quality, which may not be available in other global markets. Dates possess nutritional value, including carbohydrates, proteins, and mineral elements. They also provide the human body with the necessary thermal energy, as they contain sugar, which can make up around 80% of ripe dates. (Aleid et al. 1999; Siddiq et al. 2014). Dates are among the crops that can be processed to produce some desirable products like dates dibs and dates paste.

Dibs (date syrup) is defined as "a concentrated diabetic liquid extracted from the fruits of some dates varieties, which is the aqueous and condensed extract by the heat

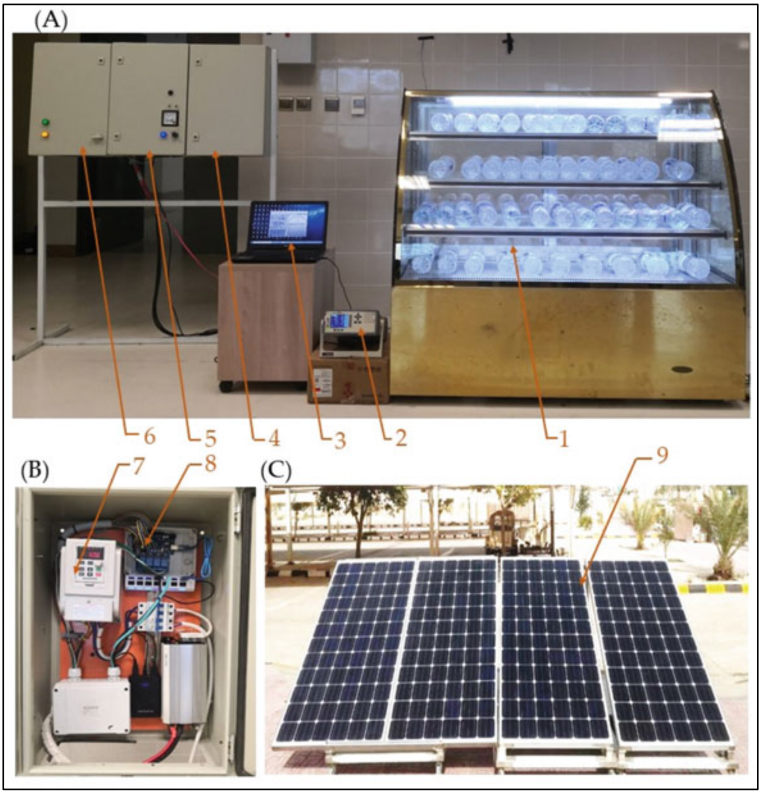


Fig. 31 Different components of the experimental setup. **A** The control panels and display refrigerator, **B** the operation control panel including inverter, **C** the solar PV array located outside the building. (1) The display refrigerator front view, (2) the multichannel temperature meter, (3) monitoring data using PC, (4) the frequency control panel, (5) the panel of electrical switches, (6) the panel of PV control, (7) variable frequency drive (VFD), (8) Arduino Mega and relay, and (9) PV modules (Eltawil et al. 2023)

of the natural contents of the fruit of the date, free of fiber, sediments, impurities, and foreign bodies, and is directly consumed or used in the manufacture of sweets and pastries" (Ibrahim 2014).

Some challenges or difficulties face the traditional method (TM) for dibs (Syrup) extraction such as long extraction period and low productivity. The insufficient presence of specialized factories and businesses has hindered the technological advancement of date conversion industries. The traditional method of dates syrup (Dibs) extraction is still in use, where it relies on heavy weights above the dates bags, and waits a long period until the extraction of syrup. Eltawil et al. (2021) designed a new electro-thermal solar energy method to extract date syrup. Two different methods of date syrup extraction were used and compared with the traditional one. In the traditional method (TM) the syrup was extracted by keeping the dates inside the

Table 3 Different specifications of the solar display refrigerator (Adapted from Eltawil et al. 2023)

Device/item	Number of units/specifications
Evaporator	• A copper tube with a 0.01 m diameter and 18.40 m length • The suction pressure as maximum value is 34.5 Pa
Evaporator fans	• Three fans (20 W power and 0.115 m diameter each), 220 V, and 0.12 A • The overall dimensions are 0.04 m in height × 0.12 m in width × 0.12 m in length
Condenser	Wire on the tube, there is a steel tube with a diameter of 0.01 m, a thickness of 0.001 m, and a length of 18 m
Condenser fans	Two fans, each measuring 0.25 m in diameter, with a power of 30 watts, operating on a voltage of 220 V and drawing a current of 0.19 amperes
Led light	Two LED lights, each with a power output of 20 watts
Capillary tube	The length of the copper is 3.49 m, with an outer diameter of 2.5 mm and an inner diameter of 1.0 mm
Drier cum filter	The diameter is 0.04 m and the length is 0.10 m
Compressor	• The text should be converted to proper English as follows: The model QB91C24GAX0 features a motor type RSIR (Resistance Start Induction Run) • A single phase, and maximum power output of 300 W at 220 V • A 9.07 cm^3 volumetric capacity and COP is 1.26 • An oil charge cooling system with a capacity of 250 cm^3 • The refrigerant is R134a, with a weight of 710 g • This model is manufactured by “Panasonic Industrial in Kuala Lumpur, Malaysia.”
Cooling Cabinet of display refrigerator	• The dimensions of the cabinet are 1.50 m in length, 0.70 m in width at the bottom, 0.19 m in width at the top, and 1.37 m in height • 4 shelves. The main body of the cabinet, front, back, and side walls are also made from tempered vacuum-insulated glass 0.02 m thick • The overall heat transfer coefficient is 0.7 Watts per square meter Kelvin • The top and bottom of the cabinet are insulated with 30 mm of foam. The total effective capacity of the object is 0.580 cubic meters
PV Array	Maximum Power is 330 Watts, Open Circuit Voltage (Voc) is 45.9 V, Short-Circuit Current is 9.26 Amperes, Maximum Power Voltage is 37.3 V, Maximum current is 8.85 Amperes, power tolerance is 0 to positive 3 percent, and the dimensions are 1956 mm × 992 mm × 40 mm.“
Charge controller	• The PC16-4015 A charge controller was utilized • The battery’s nominal voltage was 12/24 VDC • The Voc of the PV system was about 145 VDC when operating at 24 V • The maximum input power from the PV system was 1200 W when operating at 24 V • The low-voltage protection point was set at 10.0 VDC/20.0 VDC. Consequently, the peak conversion efficiency reached an impressive 98%

(continued)

Table 3 (continued)

Device/item	Number of units/specifications
Batteries	• Six deep-cycle batteries (12 V, 200 Ah each) manufactured by Hefei Greensun Solar Energy Tech Co., Ltd., with the model FM250-12 were utilized • Two batteries were connected in series for each group, resulting in three groups in total. In order to achieve a final outlet string voltage of 24 V, which is connected to the inverter's input, the outlets of these three groups were then connected in parallel • The batteries' efficiency in charge and discharge is about 0.8. The daily energy use and required number of autonomous days can be used to calculate the energy storage capacity (ESC)
Solar inverter	• The MKS-3000 (3000 V-amps or 2400 W), a device made by Sunpal Power Co., Ltd. in Hefei, China, was used to convert the DC into AC which is required for refrigerator operation • The DC input is 24 V and 100 A, while the AC output is 230 VAC, 60 Hz, and 13 A • The maximum voltage from solar modules is 145 VDC
Control System	Phase 1: "Used a traditional control system that relied on a digital temperature controller (model 230 V, XR06CX, Dixell, Pieve d'Alpago, Italy) with a fixed compressor speed (FCS) set at 230 V/60 Hz" Phase 2: "Utilize an ANN-based control system (ANN-BCS) to regulate the variable compressor speed (VCS) and fan operation of the SPDR. The block diagram of the ANN-BCS and electrical circuit of the PV system can be found in Fig. 32. The control system, when integrated with the solar PV system, consisted of a PV array, charge controller, batteries, power supply, variable speed drive system, and control panel"

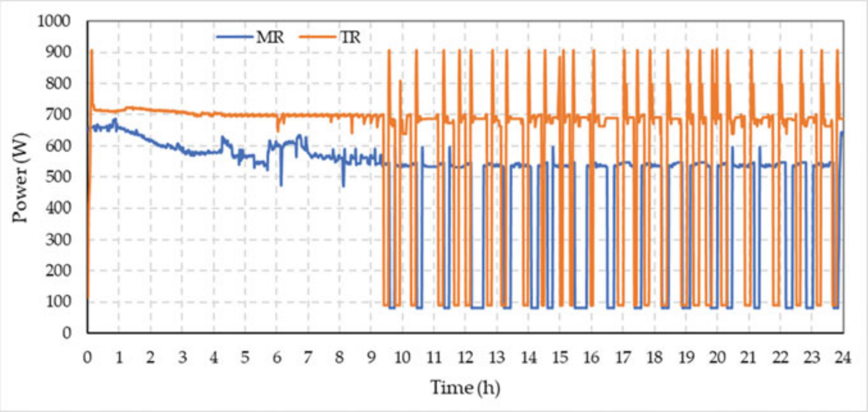


Fig.32 The solar display refrigerator (SPDR) with a modified ANN-based control system (MR) and the SPDR with a conventional control system (TR) were compared for their average daily power usage (Eltawil et al. 2023)

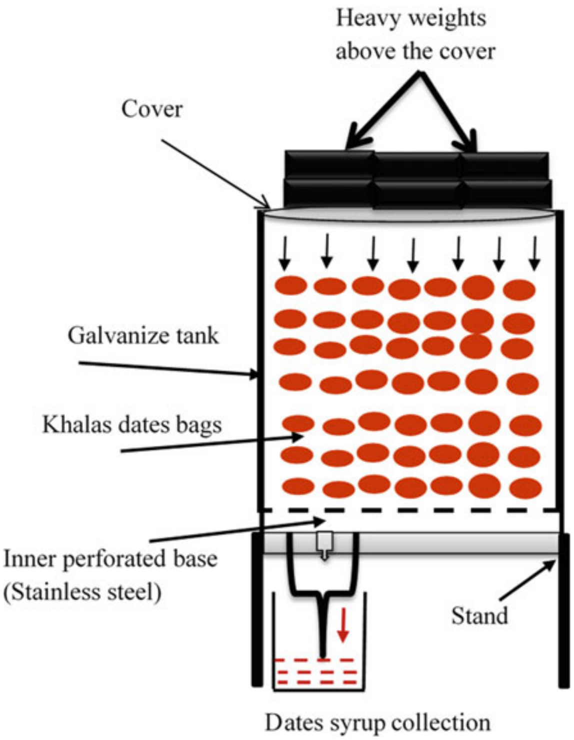


Fig. 33 Extraction of date syrup using the conventional (TM) method at room temperature

extraction tank and putting heavy weights above the cover of dates bags without any thermal treatment (at room temperature) as shown in Fig. 33.

Solar thermal energy was utilized to heat the syrup extraction medium, while solar electric energy was employed to operate and circulate the heating medium. Additionally, a manual hydraulic piston was employed to generate the required pressure (6 ± 1 and 7 ± 1 bar) to compress the dates, offering an alternative to the traditional method of using weights. Two solar heating methods were employed in the experimental setup, which consisted of a solar water collector or solar air collector along with a thermally insulated storage tank containing a rocky bed, a tank for extracting the syrup surrounded by a hot water jack or hot air jack, a water pump, and a PV system**.**

The first, was by heating with a solar water bath (Figs. 34 and 35), in which water was used as a medium for storing solar thermal energy. The second uses a solar air bath (Figs. 36 and 37) as a medium for heating with storing solar thermal energy in a rocks storage bed for use during the night. Furthermore, in both scenarios, the hydraulic piston was utilized for the process of squeezing the dates. The extraction process made use of solar thermal energy as a catalyst, which is not only renewable but also clean and environmentally friendly. To evaluate the developed heating methods, both methods were compared with the traditional extraction method used by farmers to produce date dibs.

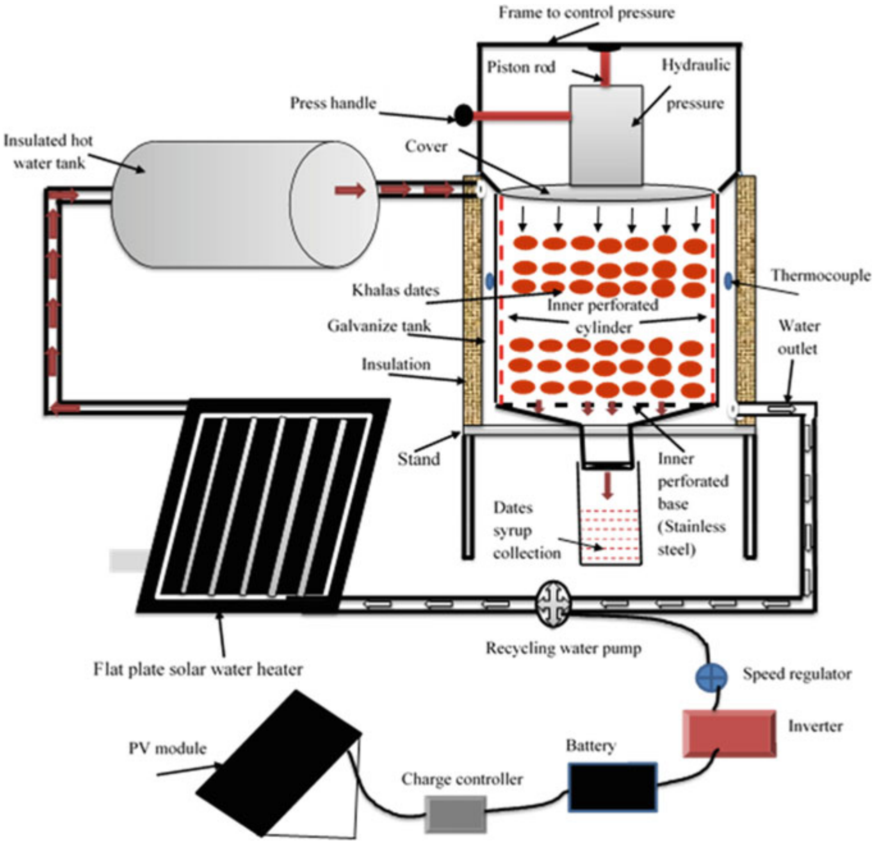


Fig. 34 Date syrup is extracted using a hybrid solar thermoelectric system (hydraulic pressure integrated with water bath heating)

The extraction tank was designed and manufactured from galvanized sheet and has a double-layer cylindrical shape (Fig. 38). The tank was isolated from the outside with foam. The space between the outer and inner diameter is utilized as a hot water bath or hot air bath to facilitate the process of extracting dibs (syrup). A cylindrical mesh basket, made of stainless steel, is placed inside the extraction tank to act as a filtering unit for the pressurized dates.

The extraction tank cover was made of heavy metal with a suitable diameter that allows it to move smoothly inside the cylindrical mesh up and down. The hydraulic jack was positioned above the tank cover and equipped with a handle to move the piston in the pressing direction, providing the necessary pressure (6 ± 1 and 7 ± 1 bar). The PV system comprises a PV module, charge controller, battery, and inverter. This system was used to supply the operational equipment with the required energy.

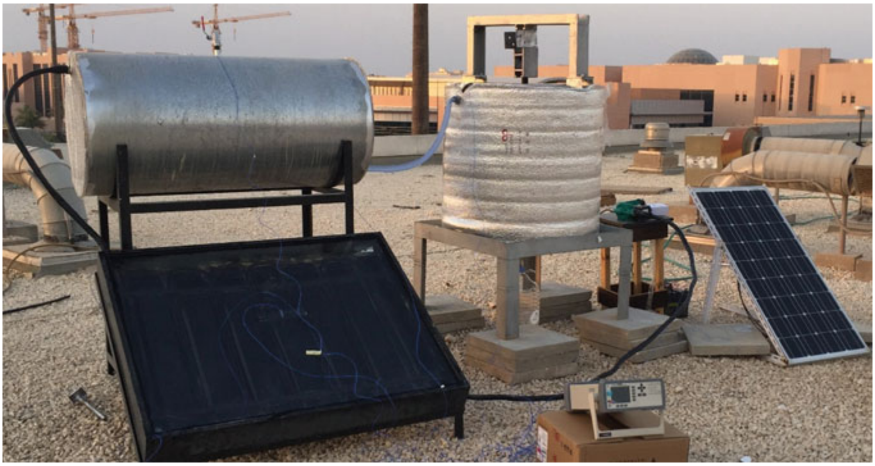


Fig.35 Hybrid solar thermoelectric system experimental configuration for making date syrup (water bath heating integrated hydraulic pressure)

3.3.1 The Extraction Process

1. Second-class Khalas dates were washed and sun-dried for about 3 hours, then packed and loaded into the extraction tank. Heavy weights were kept above the dates bags as in the traditional method (TM) while hydraulic pressure was used in the case of the electrothermal developed method
2. The water bath was filled with water that was heated using either a solar heater or hot air from a solar air collector and rocks storage bed.
3. It took around 10 hours for the dates in the extraction tank to warm up to a temperature of about 50 °C after being heated in a hot water bath (or hot air bath). The pressure started after that.
4. Two levels of hydraulic pressure (6 bar ± 1 and 7 bar ± 1) were employed for squeezing the dates. At first, the pressure was changed often; afterwards, it was changed every six hours in response to the pressure drop.
5. To maintain the temperature between 50 and 55 °C, the water in the water bath (or air in the air bath) was periodically circulated with the assistance of a control system.
6. Dibs extraction, also known as squeezing, continued until production ceased or decreased.
7. Daily collections of the created dibs were made, and they were kept in the refrigerator at a temperature of 4–5 °C. After then, samples were gathered to assess the production's dibs' quality.

The outcomes can be summarised as follows:

- The average daily PV efficiency was about 11.73%, while the PV power output was 84.91 W.

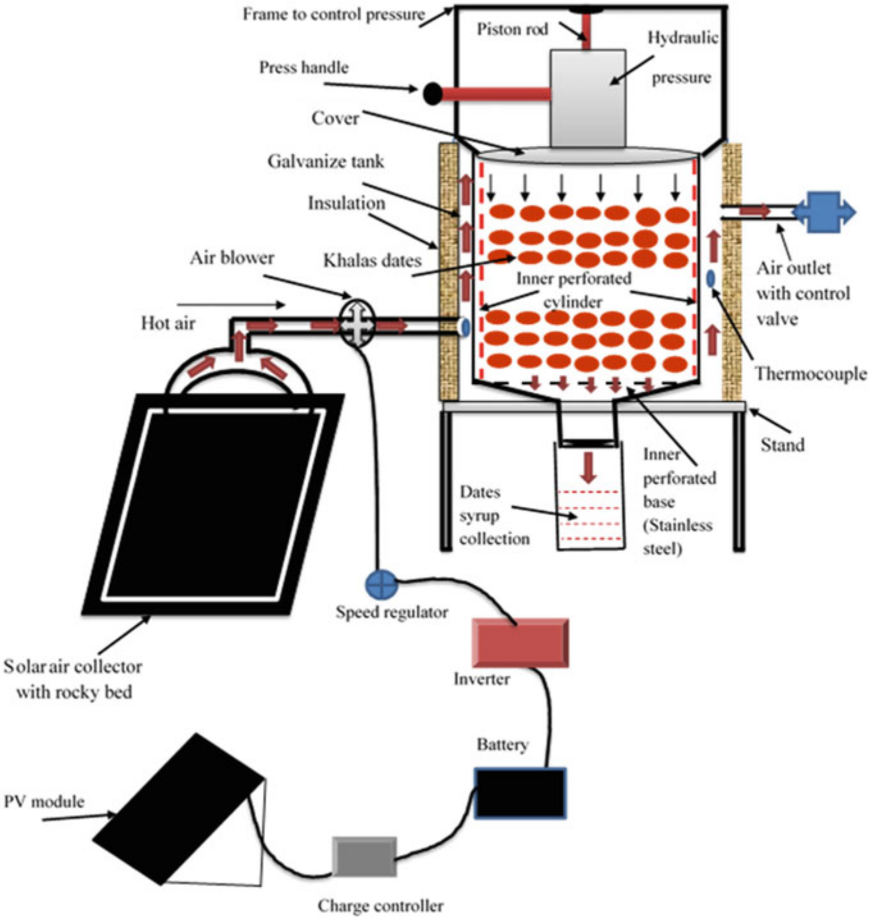


Fig.36 Using a hybrid solar thermoelectric system to make date syrup (thermal rocky bed- Air bath integrated with hydraulic pressure)

- The average power consumption of the water pump was 44.02 W while the power consumption of the air pump was 53 W.
- For the developed dates extraction systems, the temperature inside the compressed dates varied from 49° to 54°.
- The efficiency of heating dibs extraction medium using a solar water bath was 48.87%. In contrast, with a solar air bath, it was approximately 13.16%. Consequently, using a water bath is recommended.
- The developed systems shortened the extraction process period and saved approximately 38% of the time compared to the traditional method.
- In the case of water bath heating, the syrup productivity increased by approximately 28.75% and 36.66% at a pressure of 6 ± 1 and 7 ± 1 bar, respectively.

Fig.37 Solar thermoelectric system experimental setup for making date syrup (Air bath with a thermal rocky bed integrated with hydraulic pressure)

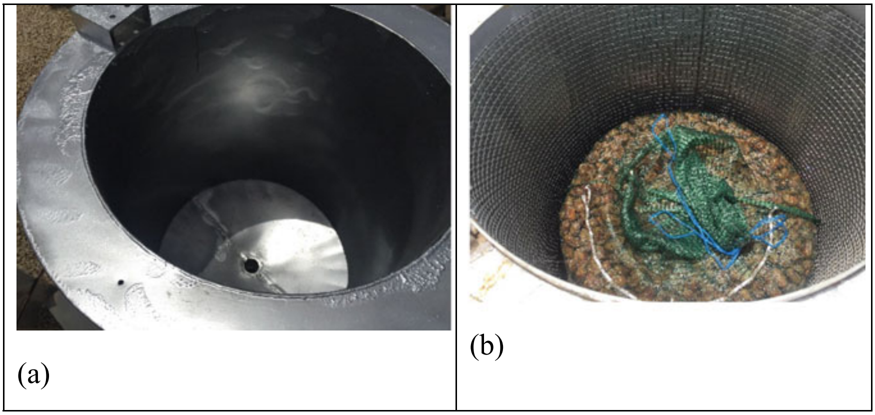


Fig.38 Dates syrup extraction tank. **a** Empty tank surrounded by the thermal bath, **b** The tank filled with perforated cylinder (extraction mesh) and some dates before squeezing

- In the case of air bath heating, the productivity was improved by 24.27% and 29.31% at a pressure of 6 ± 1 and 7 ± 1 bar, respectively.
- Increasing the squeezing pressure under the same thermal treatment led to an increase in productivity.
- The moisture content of dibs ranged from 12.8 to 13.9% (dry basis).

- The sugar content for the traditional method was 82.5%, while it ranged from 79.7 to 81.5% at a pressure of 6 bar ± 1 and from 78.9 to 82.3% at a pressure of 7 bar ± 1 in the case of heating with the water bath.
- The findings demonstrated that all procedures and treatments yielded dibs (syrup) with good color, ranging from red to yellow.
- A new method that makes use of renewable energy sources and yields high-quality date syrup is offered by the developed solar electro-thermal energy system in combination with hydraulic pressure for the extraction of date dibs, which is beneficial for remote areas.

4 Recommendations for Future Research

- Using the PV system on-grid/off-grid is advised for large-scale cold storage.
- Using both the PV system and a smart IoT-based control system is recommended for remote management of cold storage facilities.
- It is recommended to use the integration of PV systems and machine learning/artificial intelligence for smart farming.
- It is recommended to use solar greenhouses and IoT for precision farming and verticle farming (hydroponic and soilless cultivation)
- It is recommended to use machine learning and intelligent control system for enhancing the refrigerators' performance and saving energy.
- Applying a thin film roof water flow over the external cover of a greenhouse operated under the fan-pad system can lead to an additional reduction in temperature with considerable energy consumption and costs.
- Soil-less cultivation makes it possible to produce, with only little water consumption and a small amount of physical work but with great dedication and constancy, fresh and healthy vegetables in small spaces. Also this technique gives promises to solve land shrinking in cities out of cultivated lands and without increasing costs.
- Because of a lack of water, the salty or wastewater can be utilized for irrigation using a straightforward method involving solar stills that can be installed in furrows between ridges. Implementing solar stills for irrigation can help mitigate erosion caused by irrigation and decrease the amount of water needed for irrigation, while also allowing for the reuse of waste or salty water.
- To generate the necessary pressure for dibs extraction, it is advised to employ solar energy to run a fully automated hydraulic compression system. Also, to maximize syrup productivity the seedless dates (without inside kernel) should be used.

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