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Review article

Renewable energy as an alternative source for energy management in agriculture

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ABSTRACT

This study provides a high-level overview of alternative energy sources that can be harnessed to power agricultural operations, focusing on renewable energy technologies. When thinking about the overall economy around the globe, agriculture is vital. Energy is required at each step of production, from fertilizer production to fueling tractors for planting and harvesting. The high energy prices and unpredictable energy market significantly affect the input energy costs. Energy efficiency methods, when properly applied, and the use of farm's renewable energy sources could assist agricultural producers in saving energy-related costs. Renewable energy resources in the form of solar, biomass, wind, and geothermal energy are abundantly available in the agriculture sector. This review aims to explore renewable energy as an alternative energy source for efficient energy management in agriculture. It discusses the potential benefits, challenges, and opportunities associated with adopting renewable energy technologies in the agricultural sector. Our research adds value by presenting a comprehensive overview of alternative energy sources and their applicability in energy management. By highlighting the benefits and potential challenges associated with each option, we provide valuable insights for agricultural stakeholders and researchers aiming to transition toward sustainable energy practices in the sector. Better energy management is intertwined with problems that need a broader strategy than has so far been used. In a nutshell, transitioning to alternative energy sources for energy management in agriculture holds great promise for reducing greenhouse gas emissions, improving energy efficiency, and promoting sustainability in food production. However, successful implementation requires addressing technical, economic, and policy barriers while fostering knowledge dissemination and capacity building among farmers and stakeholders.

Contents

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1. Introduction

Energy is an important parameter to fulfill basic human needs from the food chain to carrying out various economic activities. These activities consist of every aspect of daily life such as household use (lighting, cooling/heating, food preparation, and preservation), agriculture (tools and machinery used for land preparation, irrigation, planting, fertilization, harvesting, and transportation), and commercial activities (transportation, building/construction, and running factories). In the agriculture sector, energy is crucial to address the challenges associated with food production. For food production, energy is needed to pump water for irrigation; run farm machinery for different agricultural tasks at the growing stage such as sowing, weed removal, fertilization, spraying and harvesting; transporting the produce; refrigeration; and drying or processing the products. Adopting and maintaining the balance between energy demand and economics acts a significant role in sustainable agriculture goals. Many under-developing countries in the world are coping with increasing demands for clean water, food and alternative energy sources amidst climate change. Due to the high level of population growth, economic and technological development, urbanization and climate change, energy demand is also increasing at a rapid pace. By 2035, the demand for energy in the world is predicted to increase by 50% (IEA, 2010). This increase in energy demand will increase electricity prices which will directly impact the agriculture sector due to its high energy demand for various agricultural activities. This high input cost to produce food from agriculture will result in increased food prices, cascading to poverty and hunger, and threatening food security, particularly in under-developing countries (Waseem et al., 2022). The intensification of energy usage in agriculture and high input cost could be addressed by adopting renewable sources and better energy management practices.

Adoption of renewable energy sources for agricultural-related tasks will result in improved energy utilization, food security, and environmental change for ecological agriculture goals. On a global scale, the energy challenges in agriculture vary depending on the level of development, geographical location, and agricultural practices. Developing countries often face more significant energy constraints due to limited infrastructure, inadequate access to modern technologies, and higher reliance on manual labor. In contrast, developed countries grapple with optimizing energy use, reducing emissions, and integrating renewable energy solutions. To achieve reliable and environmentally friendly renewable energy alternatives, the energy sector needs comprehensive transformation by adopting renewable sources. Some major energy problem types and challenges in agriculture are poor rural infrastructure, limited biomass utilization, heavy fossil fuel dependency, heavy reliance on energy for irrigation, and limited access to modern energy. Based on United Nations' sustainable energy goals, it needs to double its renewable energy use by 2030 (Griggs et al., 2013). To achieve the goal, research must also be focused on the nexus of food, water, and energy and the impact of expanding renewable energy on these sectors. Renewable energy usage in agriculture will help to address and focus on these sectors discretely, the demand for energy and food is directly dependent on an increase in population and climatic changes. Renewable energy's use in agriculture and efficient energy management practices will help to relieve grid load and reduce input costs which ensure food security issues.

This paper comprehensively reviews and explores renewable energy as an alternative energy source for efficient energy management in the agricultural sector. While previous studies have touched upon renewable energy technologies in agriculture, this review paper goes beyond by providing a high-level overview and analysis of multiple renewable energy sources, namely solar, biomass, wind, and geothermal energy, tailored explicitly for agricultural operations. The paper emphasizes the potential benefits of adopting renewable energy technologies in agriculture and addresses the challenges and opportunities associated with their implementation. The research offers valuable insights for agricultural stakeholders and researchers seeking to transition toward sustainable energy practices in the sector by presenting a comprehensive overview of alternative energy sources and their applicability in energy management. By offering a comprehensive overview, this paper contributes to the existing literature by presenting a valuable resource for stakeholders and researchers interested in advancing energy management practices in agriculture and fostering sustainable development in the sector.

2. Energy demands in agriculture

The consumption of energy in the world is speedily increasing, and that increase is met by the availability of fossil. While global reserves of these fossils are rapidly diminishing which is causing high energy costs due to an imbalance in supply and demand. Moreover, the use of this fossil causes high carbon emission and causing global warming. This increase in energy prices and global warming will have a direct impact on agriculture. Future agriculture farms should be self-reliant to offset the high energy cost and global warming. This self-reliance could be achieved using renewable energy sources and efficient nutrient recycling, as shown in Fig. 1a and b. The energy demands in agriculture include fertilization, irrigation, and tools and machinery used for land preparation, planting, harvesting and transport. Energy in agriculture can be used directly or indirectly (Schnepf, 2004). Direct energy includes energy consumed directly in various agricultural activities, for instance, to operate tools and machinery for different farm activities, vehicles used for transportation, and drying and refrigeration equipment (Zhou et al., 2023a,b). While indirect energy use includes the energy needed to produce fertilizers,

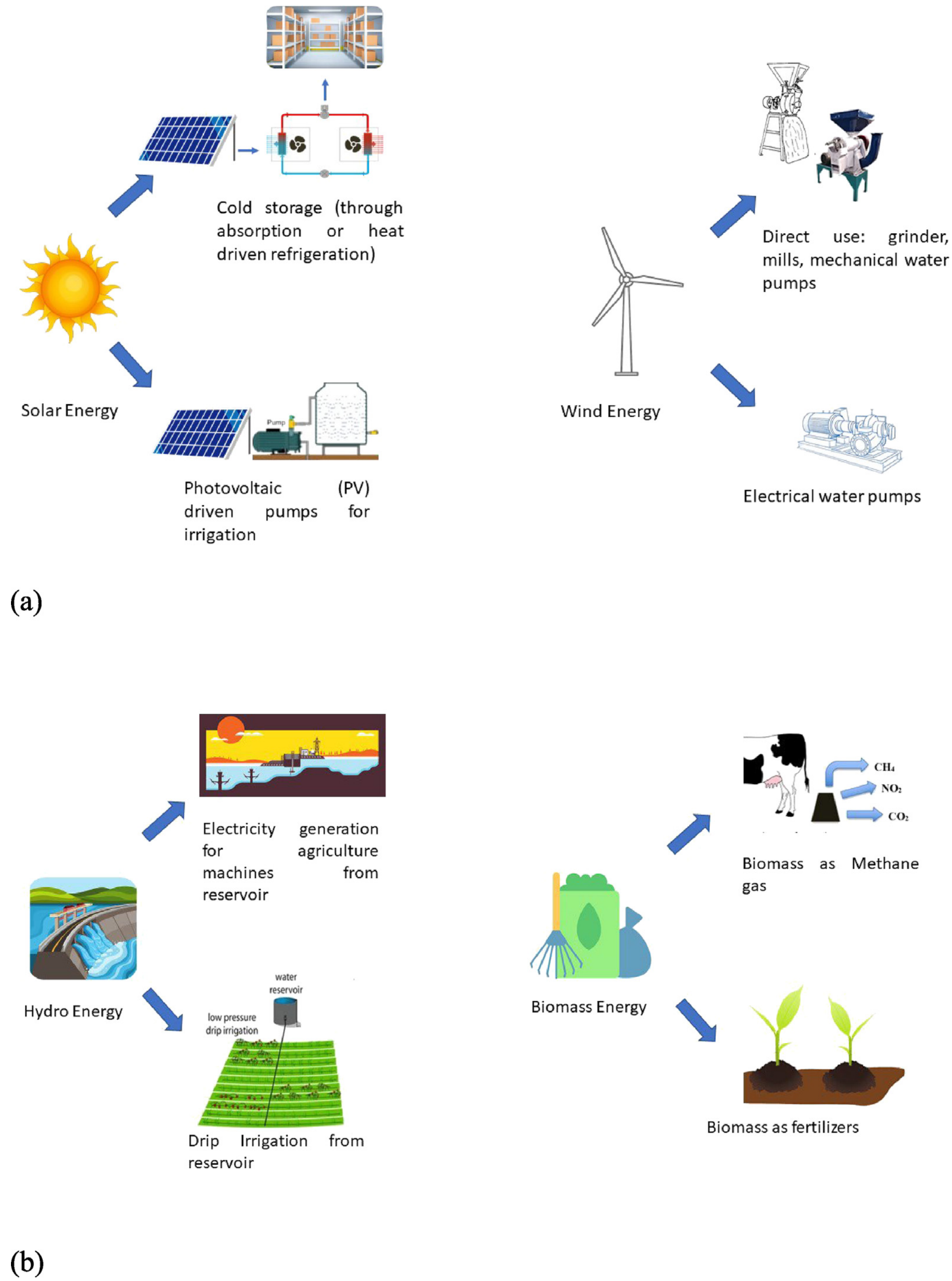

Fig. 1. (a). Usage of wind and solar as renewable energy sources to run different agricultural machines; and (b). Efficient use of hydro and biomass as renewable energy and recycling to agriculture waste/produce.

chemicals, and pesticides used in agriculture. For example, during 1961–2008, the use of fertilizers in agriculture increased six times to fulfill the growing demand for food with the increase in world population while the cropping land area almost remained the same during the same period (Faostat, 2010). Around 94% of the total energy demand in agriculture is needed to produce ammonia (Mikkola and Ahokas, 2010). Also, around 1.2% of total world energy is consumed to produce fertilizers for agriculture. Production of these fertilizers is heavily reliant on fossil fuel (here natural gas). It is expected that the population of world will be increased to 9 billion in 2040, which means the use of fertilizers will further increase many folds to meet the growing demand for food hence increasing the demand for energy for the agriculture sector. Another major source of energy consumption in agriculture is the energy consumed by the tools and machinery used for various agricultural activities. The green revolution in the 1960s was inspired by farm activities replacing the human labor animal used. These farm-mechanized activities use tractors, pumps, motors, and lights to perform various tasks and use the electricity from the grid to optimize and increase agriculture production. The electricity from the grid is heavily reliant on fossil fuels. Hence the increase in mechanized activities in agriculture causes the increased usage of fossil fuels. For example, an irrigation system is very important in agriculture production from the viewpoints of meeting crop water requirements (Li et al., 2020; Zhao et al., 2022). For this purpose, water pumping from ground or surface storage is critically needed for various activities such as irrigating crops, supporting livestock and cleaning. The cost of water pumping depends on the availability of water, use pattern and energy. Traditionally water pumping is implemented using direct fossils such as diesel or petrol, or electricity from the grid. Heavy consumption of water in agriculture and household use causes rapid depletion of groundwater sources; hence groundwater level is decreasing. The decrease in groundwater level needs heavy energy to pump the water for irrigation. Hence the demand for energy usage in agriculture is increasing and causing the load on the electricity grid. Additionally, with the rapid population growth, food security-related concerns are also growing rapidly. One of the major food security concerns food wastage. Food waste occurs in every stage of food production. Different refrigeration and drying techniques are used to minimize food wastage. For example, the drying method has been adopted to reduce food wastage and to store the product for a longer period. The drying process involves heat and mass transfer hence is high energy demanding process. That drying process can be adopted with the use of renewable energy sources to reduce the grid load, making agriculture self-reliant and bringing the agriculture input cost. In short, the usage of renewable sources of energy in the agriculture sector and efficient energy management practices will help (Sharma et al., 2009) relieve grid load and reduce input costs which ensure food security issues.

3. Energy efficiency opportunities for the agriculture sector

The conversion of energy from one form to another is very necessary to run a process or a task. During this energy conversion process, energy loss is imminent due to various factors. For example, in agriculture, to run water the pump for irrigation, the first chemical energy of fossil fuel is converted to mechanical energy to power the pump shaft. Then, this mechanical energy is used to uplift the water at height by converting it to the potential energy of water. The efficiency of converted energy is the ratio of output energy and input energy. In the case of the above example, input energy is the fossil fuel used by the pump and output energy is the water discharge of the pump. Efficient utilization of energy is critically important to decrease energy consumption and achieve sustainability in energy management practices. Globally, 30% demand for energy is from the agriculture and food sectors (Day, 2011). Therefore, adopting energy-efficient approaches in agriculture is essential to reduce heavy reliance on energy and reduce the input cost to make the agriculture sector more competitive to meet the growing demand. As discussed above, the agriculture production cycle is heavily dependent on fossil fuels from manufacturing fertilizers to running machinery for field operations. This huge demand for energy in agriculture and its dependence on the grid can be reduced by using renewable energy sources. Photovoltaic systems being used in residential buildings could be a potential solution to mitigate energy crises for promoting sustainable agriculture (Ge et al., 2022; Huang et al., 2023; Wang et al., 2022). These sources are profusely available in the agriculture sector. For example, crops grow in areas where there is sufficient sunlight around the year to support the growth of plants. It means, abundantly available sunlight energy can easily be harnessed using solar panels that can be used to run various agricultural equipment (i.e. water pumps for irrigation). Generated electricity from solar panels can also be used to run various refrigeration and drying units that are commonly used in agriculture to store and increase the shelf life of agricultural produce. Moreover, direct sunlight can also be used for cooking, drying, and water heating using solar cookers, solar dryers, and solar water heaters, respectively. Additionally, fuel cells can enable efficient and effective utilization of hydrogen energy in the agriculture sector because of their flexibility and interoperability (He et al., 2022; Quan et al., 2023; Yu et al., 2023a,b). Various applications of renewable energy resources in different agriculture sectors are discussed in Table 1. Wind energy is another renewable energy resource that can be harnessed by farmers to power their farms. In areas where wind energy is abundantly available farmers can generate electricity using wind turbines (Chen et al., 2022; Sun et al., 2023; Zhou et al., 2023a,b). This generated electricity could be used to power heavy machinery involved in agricultural operations and processing the of agricultural produce. Another huge source of renewable energy in agriculture is bioenergy source which agriculture has in abundance. According to studies, alone bioenergy can meet around 30%–40% of the entire world's energy needs by 2050 (Holm-Nielsen et al., 2006). The raw material needed for bioenergy is available in surplus and cheap in the agriculture sector in the form of agriculture, food livestock, and municipal solid waste. Utilization of biowaste in agriculture can help to produce biogas which then can be used for generating electricity. Also, biowaste can be utilized as a fertilizer to reduce the heavy dependence on commercial fertilizers. Along with effectively using the renewable sources already available in agriculture, pursuing electricity conservation practices could also help to reduce the input cost for agriculture. For example, replacing the old and high electricity consuming devices (i.e. bulbs, motors, pumps, etc.) with the latest energy efficient devices could also help to save electricity. This efficient utilization of renewable energy sources in agriculture coupled with energy-efficient management practices could help to achieve sustainable agriculture goals.

4. Application of renewable energy in agriculture

Currently, renewable sources are commonly used in different sectors to meet their energy desires. In agriculture, renewable energy can be used for pumping water for irrigation to dry food to increase its shelf life. It may shed light on issues like diminishing fossil fuel reserves, rising costs, negative environmental impacts, and so on, that have arisen as a result of our reliance on fossil fuels. Using renewable energy in agriculture will help overcome these problems, which will lead to higher profits and more independence for agriculture in the long run. Moreover, these renewable energy sources can be harnessed for a longer period without depleting any of the natural resources. This will significantly help the energy security of the agriculture sector. In the next sections, we will look at the many ways in which renewable energy sources like bio-energy, wind, solar, and geothermal might be put to use in agriculture.

4.1. Solar energy

The sun provides most of the energy used by humans on Earth. So-called "solar" energy is harnessed directly from the sun. Renewable energy is sometimes known as eco-friendly power, green power, sustainable power, or alternative energy. Very little of the sun's energy actually reaches Earth as radiation because most of it is absorbed by the surrounding stellar environment. In only one hour, the sun's rays reach Earth's surface with more energy than can be generated by any combination of conventional energy sources like fossil fuels, hydropower, nuclear power, etc. When compared to a nuclear power plant, which can create 1000 MW of electricity by converting 0.130 kg of nuclear fuel in one year, the sun's surface transforms around 4,000,000 t of solar fuel into energy each second. The average amount of solar energy received by a square meter of Earth's surface is 1366 W (Lindsey, 2009);

Table 1
Applications of renewable energy resources in different agriculture sectors.

Sr. No.	Sector	Renewable energy source	Technology	References
1	Irrigation	Solar panels assembly	Fuzzy logic and cloud tech	Sudharshan et al. (2019)
		Solar photovoltaic cells	Pump used for irrigation	García et al. (2019)
		Wind onshore	RO (Reverse Osmosis) of water for irrigation	Caldera and Breyer (2019)
		PV panels	RO (Reverse Osmosis) of water	Shoeb and Shafiullah (2018)
			Islanded microgrid for pumps	
		Wind energy	Desalination system	Serrano-Tovar et al. (2019)
		Geothermal energy	Field irrigation, heat pumps	Alberti et al. (2018)
2	Greenhouse management	Photovoltaic (PV) generator	Ventilation and heating wind turbine	Riahi et al. (2021)
			Ventilation and heating	
		Photovoltaic and wind	Wind-PV hybrid generation system, modeling, simulation and analysis	Jomaa et al. (2017)
		PV panels	Photovoltaic greenhouse tunnel	Marucci et al. (2018)
3	Monitoring/ Regulating systems	Solar-powered prototype nodes	Precision agriculture (pa), wireless sensor networks, internet of things (IoT)	Sadowski and Spachos (2018)
		Photovoltaic (PV)centrifugal and positive displacement pump	Humidity sensors and global system for mobile (GSM) module	Waleed et al. (2019)
		Solar panels	Wireless sensor networks	Sharma et al. (2019)
4	Water pumping system	Solar PV water pumping systems	Brushless DC (direct current) motors, centrifugal and positive displacement pump Solar thermal water-pumping-systems Vapor power cycles Wind energy Wind powered synchronous generators Biomass water pumping systems Biomass gasifier dual fuel powered diesel engine coupled with a centrifugal pump	Gopal et al. (2013)
		Hybrid renewable energy water pumping systems	The solar–wind hybrid system	
5	Drying	Solar dryers	Thermal energy storage (TES) Pebble-bed TES	Qu et al. (2022)
		Solar drying system	Phase change material (PCM) based thermal storage	
		Geothermal heating	Heat extraction from geothermal wells Biomass	
		Biomass	Hot air is produced from biomass combustion and circulated through the dryer.	
		Solar	PCM (pulse-code modulation) integrated heat pump dryers	
		Solar thermal energy	Heat pump based solar microwave drying	
6	Desalination	Solar collector, solar still	Solar assisted desalination system	Sohani et al. (2022)
		Air solar heater	Humidification-dehumidification desalination system	Rahimi-Ahar et al. (2018)
		Geothermal energy	Multi-effects distillation	Alkaisi et al. (2017)
		Wind	Membrane distillation	
		Wave and tidal	Reverse osmosis	
7	Tractor Vogt et al. (2018)	Solar radiation	Tractor propelling by energy from solar cells	Vogt et al. (2018)

(continued on next page)

Table 1 (*continued*).

8	Refrigeration	Photovoltaic panel	Vapor compression cycle	Fekadu and Subudhi (2018)
		Solar thermal collector	Steam jet cycle	
		Solar energy	Adsorption refrigeration technology	Goyal et al. (2016)
9	Distillation	Solar-driven	Evaporative cooling	Kabeel et al. (2017)
		Solar energy	Direct contact membrane distillation	Shim et al. (2015)
10	Bakery	Solar	Metal hydride based thermochemical energy storage system	Ayub et al. (2020), Meyer and von Solms (2018)
			Mixer proofer oven	
11	Seed sowing	Solar controller	Radio frequency based sowing machine	Devaraj et al. (2020)
12	Roasting	Solar	Batch-type direct roasting	Majeed et al. (2022a,b)
			Continuous-type thermal-oil based roasting	Raza et al. (2019)

however, this may vary depending on latitude (Cocks, 2009). A critical first step in harnessing solar energy is determining how much energy is available from the sun in a given area of the Earth. The economic and social progress of a country depends on how well it can get a reliable and cheap supply of energy (Fatai et al., 2004; Muneer et al., 2006). Most of the current global energy demand is being met by consuming conventional fossil fuels. Only 9% of the world's energy requirements are fulfilled by solar and wind energy. The global energy mix for the year 2019 revealed that solar energy increased along with other renewable sources by up to 24% which is almost twice as much when compared with wind energy for that specific year (Kapoor et al., 2019).

The technology used today in agricultural farms varies from that used in the past. Agricultural farms require a continuous supply of energy to operate farming vehicles and various machines which are normally produced by existing fossil fuels. With the ever-increasing demand for energy due to the advancement of technology and the growth of the population has led to the exhaustion of conventional fossil fuels at an alarming rate. Scientists and researchers, therefore, have diverted their attention to investigating new alternative renewable energy sources to achieve sustainable agriculture. This will not maximize crop productivity but will also mitigate environmental impacts (Kaushık and Chel, 2011). There are many alternative renewable energy resources among which solar energy stands out as it is readily available all around the globe. Current agricultural practices are also a cause of greenhouse gases (GHGs). Utilizing solar energy hinders the emission of GHGs leading to developing countries using this resource. It can be used for various purposes such as farm cultivation, pumping for irrigation, heating, drying or value addition of agricultural products, greenhouse cultivation, and ventilation hence reducing detrimental effects on the environment. Various devices which absorb solar energy are currently being used for agricultural applications. To utilize the abundantly available solar energy, two methods are commonly used for obtaining electrical energy from solar energy: solar capture heating systems and applying solar panels (Photovoltaic, PV) systems (Hoogwijk, 2004). Sun rays are converted to electrical energy directly in PV systems by using semiconductors, but their current state requires further research in terms of efficiency. Various other ways of utilizing solar energy are depicted in Fig. 1. Solar energy can be used in agricultural systems and some of them are as follows.

Since a fast-growing renewable-based method, photovoltaic solar technology offers a potentially viable alternative for sustainably powering agricultural activities, as it can provide both electricity and heat requirements in agriculture via the use of photovoltaic-thermal (PVT) systems (Singhal et al., 2018; Tariq et al., 2021). Although large-scale, centrally located PV power plants are more practical (financially and technically), distributed PV systems are preferred in cultivation systems like growth or greenhouse rooms and small-scale remote access farms (Devaraj et al., 2020). Renewable energy sources like wind and solar can be used to power farm vehicles in a way that is good for the economy and the environment (Balasuadhakar et al., 2016).

4.1.1. Solar-powered irrigation

Improved crop quality is largely attributable to the fact that irrigation significantly raises the amount of "fresh mass" in irrigated crops. The amount of water needed for irrigation purposes in order to keep crops alive has grown in recent years, as the world's population has risen rapidly and urbanization has progressed, water management has emerged as a major issue (Mahfooz et al., 2022). Crop irrigation using solar-powered pumping devices is an option worth exploring in developing countries like India and Bangladesh. Due to the soil's water-lifting qualities and its ability to equally distribute water in command areas, solar pumping systems are also growing in popularity in rural areas for low-lift minor irrigation. Irrigation accounts for around 35% of the use of solar pumps in Bangladesh (Hossain et al., 2005).

Solar irrigation, one of the most mature uses, is widely used to increase water access, allowing for many cropping cycles and enhancing resistance to shifting rainfall patterns. As the land area under irrigation grows, the use of solar irrigation displaces present and future fossil fuel consumption. As a result, emissions are reduced. Solar-powered water pumping has 95% to 98% fewer life-cycle emissions than pumps fueled by grid energy or diesel fuel. Solar-powered irrigation, in particular, allows for the decentralized and ecologically friendly meeting of energy demands for water pumping. Indeed, energy-efficient and cost-effective solar water pumps have the potential to transform the lives of many farmers in the world (Feng et al., 2022).

4.1.2. PV-based pumping system

Solar-based pumping systems have been installed for irrigation purposes. It can be used to lift water from canals and distribute the water into areas for irrigation purposes. Solar-powered pumping systems for agriculture in impoverished nations may be a potential method of watering crops. A solar pump is seen as a viable choice for pulling irrigation water from rivers, canals, and ponds (Parmar et al., 2021). In underdeveloped countries, where there is a larger population of farmers, the higher cost of electricity prevents its widespread adoption. Solar photovoltaic pumping systems may be put to use in poorly infrastructured areas with less advanced technologies availability (Patil and Gawande, 2016).

4.1.3. Spraying and sowing machines based on solar energy

Pesticide sprayers using solar energy are designed for small-land owing farming to enhance crop productivity. These machines can be easily handled and moved owing to their overall small design. They also possess rechargeable batteries along with PV panels. As spraying activities are usually performed during the day, these machines can be charged from direct sunlight as they are being used. Machines used for seed spreading and sowing can also prove to be beneficial for small farmers and in areas where conventional machines do not have easy access. Hence automatic solar-based sprayers and sowing machines will enable small farmers to quail from traditional heavy agricultural machinery (Naween, 2009). Today farmers are provided with alternative options to use radio frequency (RF) controlled machines for spraying pesticides and seed sowing which run on renewable sources. The solar-based machines work using Bluetooth where they sow seeds at a specified depth and distance apart (Mühlbauer, 1986).

4.1.4. Solar-assisted drying

One of the most widely used applications of energy gained by solar in agriculture is value addition via drying systems. Solar dryers are accessible in numerous forms, sizes, and arrangements. Different dryers are available for drying different products such as carrots, grains, mushrooms, and potatoes. Based on heating arrangement dryers are categorized into active and passive dryers. Dryers that transfer heat from solar energy via external means (i.e., pumps and fans) are known as active dryers. Whereas in passive dryers, heat flow is carried out by natural means via buoyancy force or wind pressure and in some cases by combining both (Pohekar et al., 2005). Solar drying technology helps to dry the product in a clean environment and makes the product able to meet national and international standards. A solar-based tunnel dryer was developed by Kalogirou (2004) that is used to dry chilies and paddy rice. Saxena et al. (2011) worked on the optimization of a solar tunnel dryer by drying chilies in Bangladesh. Despite this, a solar dryer is also designed for the drying of coconut (Scheffler et al., 2006). Solar dryers are efficient in reducing the consumption of fossil fuels, processing time, and area for work (Munir and Hensel, 2009). Food commodities such as meat dried in solar tunnel dryers in hot climatic conditions by Mewa et al. (2019) and they found that the drying time of these commodities decrease by up to 40% and the efficiency of the collector was 23.5%–36%. A solar tunnel dryer has also been developed that act as a greenhouse and is used for the drying of agricultural products (Rincon Mejia and Osorio Jaramillo, 2000). Thus the use of a solar tunnel dryer for the drying of product is the best method that not only dries the product but also maintains quality (Ayub et al., 2018). Quality is an important term during the drying of these products so that they can be preserved for a long time. As a result of severe electricity shortages in these nations, solar-powered dryers are increasingly being used to preserve food supplies. To combat the ever-increasing cost of fossil fuels, more and more farmers are turning to this renewable source of energy to dry their crops. Even though it is been around for a while, the method is still widely used in many nations today. Lack of information about appropriate measures that assist in decreasing spoilage and extending the shelf life of agricultural goods is the primary cause of this waste. Drying is a time-tested method that has been used for centuries to lower a product's moisture content. The majority of agricultural and horticultural goods are dried using this method (Mondal and Datta, 2008).

4.1.5. Solar bakery

The baking process is highly energy-consuming in the food industry and has become more challenging, especially for developing countries. Heat energy is used on an industrial scale in a bulky amount for heating purposes. Cooking is an important process and it takes a big portion of energy consumption especially in developing countries (Pohekar et al., 2005). The baking industry consumes more energy in huge amounts than any other cooking process. The use of firewood and fossil fuels causes deforestation and environmental pollution. Therefore, there is a need to design environment-friendly technologies in food industries to overcome energy crises.

Solar-based thermal energy is a substitute for primary-costive energy sources and has been found very effective to meet the energy demand in the baking industry. Various types of concentrating (heliostat and parabolic plates) and non-concentrating (vacuum tube collectors and flat plate collectors) collectors that work on solar energy are used widely in the world (Kalogirou, 2004). However, these types of collectors are not found suitable for high-temperature required agricultural processes. A solar-based solar-boxed cooker is developed by Saxena et al. (2011) that reduced the cooking time by up to 20 min and also the cooking power increased by up to 79.80 W.

Fixed-focus concentrators are also developed for moderate to high-temperature cooking, baking, heating, roasting, and power generation (Scheffler et al., 2006). The concentrators have a paraboloid focus that focuses all the incident beams on a fixed receiver (Munir and Hensel, 2009). Thus making it effective in the baking process. The applications of solar-based thermal energy in cooking are easily manageable but its application in baking requires more care because of the high temperature. The study on 2D and 3D ray tracing processes was also done for elevating solar-based hot plates (Rincon Mejia and Osorio Jaramillo, 2000). The high range temperature such as 250 °C was attained at a half-acceptance angle of 5 degrees that concentrate the sunlight without any stalking for about 40 min. These temperatures are highly suitable for the cooking process. Rincon Mejia and Osorio Jaramillo (2000) also explained the design, working, and outcomes of the solar-based cooker. The application of curved mirrors in solar cookers makes it an innovative design and also makes it able to perform the functions of an oven, additionally, the capability to fry. Heat and mass transfer and different chemical reactions are the phenomena that are involved in the baking process. Since baking process performance depends upon the time–temperature changes and moisture content distribution especially during chemical reactions thus, it is very difficult to predict (Mondal and Datta, 2008). In order to heat the air circulating in the baking chamber using a photovoltaic-controlled fan, a solar bakery unit was designed. This unit consists of a 10 m^2 Scheffler reflector that focuses all the beam radiation on a secondary reflector. The average energy usage ratio was calculated to be 45%. The research lays the groundwork for making a low-cost solar oven that works well and can replace traditional ovens.

4.1.6. Solar distillation for oil extraction

By evaporating the volatile essence, distillation purifies oil extracted from plant sources. Essential oils are the volatile byproducts of the distillation of plant materials, whether by steam or water and include a complex variety of chemical components responsible for their defining features. Essential oils from medicinal and aromatic plants have been the subject of a large number of controlled laboratory experiments. Different types of tree components are used to extract these oils. But the oil that is pressed from its leaves is the most prized of all oils. A range of 0.1% to 7% essential oils may be found in the leaves of different plant species (Munir and Hensel, 2010). Solar-based distillation system effectively utilizes heat radiation thus proving itself an energy-saving process. The cost of production on conventional distillation systems is very high in Pakistan because of the high prices of gas.

On the other hand, a solar-based distillation system is very cost-effective, coherent and energy-optimal (Bachheti et al., 2011). A solar-based distillation system was designed by Hussain et al. to process the medicinal and aromatic plants as shown in the figure. He distilled Eucalyptus Camaldulensis and Eucalyptus Citriodora, solar-based essential oils by using the conventional and solar-based distilled systems and found that the quality and quantity of oil obtained from both processes were the same (see Fig. 4).

4.1.7. Solar-assisted refrigeration and cold storage

Despite the high production of food crops, food security is still a big challenge for development. Post-harvest losses and government policies are one of the reasons for this problem. Climate conditions have more effect on the shelf file of agriculture crops. Some fruits and vegetables have short shelf-life and need special care (Majeed and Waseem, 2022). Most of the post-harvest losses occur because of improper handling, storage and transportation of food (Malle and Schmickl, 2007; Zhang and Datta, 2006). Due to this, a large part of perishable products is lost at the farm level. Drying and cooling of fruits and vegetables are considered the most convenient methods for the storage of these commodities (Lantitsou and Panagiotakis, 2017; Salamon et al., 2021; Zhao and Zhang, 2014). The drying process reduces the moisture level and decreases the microbial activity and enhances the shelf life of the food (Fathi et al., 2022). Despite its advantages, this process also has some disadvantages. It negatively affects the color, texture, and taste of food products (Afzal et al., 2017; Chahomchuen et al., 2020; Radwan et al., 2020; Raza et al., 2021). In the cooling process, the temperature of the commodities is kept very low. At this low temperature, most of the microbes cannot survive hence microbial activity decreases and shelf life increases. This technique is very useful for the preservation of perishable products since it does not deteriorate them.

Conventional cold storage techniques require a high amount of energy for the refrigeration system. That is why this technique is not in common practice among farmers. On the other hand, cold storages are also not easily available in all areas (Degirmencioglu et al., 2019). Therefore, it is difficult for average farmers to sell products with low profits. Moreover, this technique is commonly used at a commercial scale to preserve perishable food. As the moisture content of fruits and vegetables is very high, their spoilage starts just after their harvesting (Ali et al., 2002; Sipahioglu and Barringer, 2003). To decrease the losses due to spoilage, it is necessary and useful to store them properly after harvesting. In this regard, solar-based cold storage at farm significantly reduces post-harvest losses as well as operational cost (Zhang et al., 2018). To reduce post-harvest losses, solar-based storage is designed to facilitate the farmer in fields.

Solar-based refrigeration and air conditioning systems can save energy up to 40%–50% (Diaconu et al., 2011). In under-developing countries, post-harvest losses are very high. The use of solar-based energy in hot regions like Pakistan for the preservation and processing of perishable foods is very effective, especially in villages where access to grid supply is very difficult. Pakistan receives profuse amounts of solar radiation all over the year (Ghafoor et al., 2016). The average availability of solar radiation in Pakistan is 5–7 kWh/m^{2}d and the country takes 19 MJ of energy on average each year (Sheikh, 2010). Thus solar energy proves itself an effective technology in order running cold storage.

The effectiveness of solar-based energy for the cooling and storage of materials has been discussed in the literature. Otanicar et al. (2012) discussed the impact of solar-based cooling on the economy and environment. He states that the initial cost of the solar system is a major hurdle in the extensive use of solar cooling technologies. However, it is predicted that capital investment in solar-based electric cooling will be the least in 2030 because of the high initial cost and COP (coefficient of performance) values of the vapor compression unit of refrigeration. Since the COP values are already very high, a combination of the refrigeration system and PV technology will reduce operating costs. The applications of solar-based cooling systems will be common with the decrease in the value of PV technology. Two different types of energy storage are used in a PV-based cooling system: a battery bank and a cold water storage system (Wang et al., 2017), both the battery storage capacity and the cold storage capacity are heavily impacted by the chiller schedule. Depending on the battery and water storage tank, the TSE (total system efficiency) may increase from 6.73 percent to 10.27 percent when used in cold storage. Solar-powered, battery-backed, vapor-compression refrigerant-filled cold storage (capacity: 6–8 tons) (2.5 TR) was reported in Singh et al. (2018) and Amjad et al. (2021) discussed a cold storage unit having a capacity of 2 tonnes. He used a hybrid solar system which consists of a PV system, a hybrid inverter and a battery bank having values of 4.5 kWp, 5 kW, and 600 Ah respectively. They also used 2 tonnes of vapor compression refrigeration system coupled with three cooling pads that help in storing cooling. He stored potatoes for three months at 8 °C the values of solar irradiation recorded were 5–6 kWh/(m^{2}d) with an average power peak value of 4 kW. He also used a variable frequency driver to measure the torque load. AC (air conditioning) was used by the author in the system with COP 4.6. The system consumed an average of 15 kWh energy, 4.3 kW obtained from grid and 10.5 kWh from the solar system (see Fig. 5).

4.1.8. Greenhouse heating using solar energy

Normally, greenhouses use the sun to fulfill their lighting requirements for photosynthesis but they do not use this source for heating purposes. Instead, oil and gas are used in winter to maintain the temperature requirements for their growth. Whereas solar-based greenhouses (SGHs) are made to utilize the full potential of solar power to meet both the requirements of lighting and heating. These signs are mitigated harm caused by excessive ambient sunlight during hot sunny days.

4.1.9. Solar-powered tractors

The tractor is considered the most important machine in farming to enhance productivity. Normal tractors run on oil which not only increases the cost of farming but also harms the environment by generating carbon dioxide. Tractors are used to mechanize farm tasks such as planting, ploughing, reaping, and harvesting (Munir and Hensel, 2010). Solar-based tractors, therefore, become a viable option thatmillion can work during daytime and nighttime by using PV modules and batteries respectively. Currently, the development of solar-based tractors is at the initial stage but their prospect in agriculture is bright (Godfray et al., 2010).

4.1.10. Fertilization using solar energy

Today farmers use fertilizers to boost crop yield. In agriculture, ammonia being the most important chemical plays a crucial role in fertilizer production using the thermochemical Haber-Bosch process. This process produced 140 million tons of ammonia (NH_3) each year. The Haber-Bosch process is very energy-demanding, using up about 2.5 oxyjoules annually. The method uses hydrogen derived from methane, which in turn produces 340 million metric tons of CO_2 annually (Maphosa, 2020). Due to huge capital investments to set up fertilizer plants <100 plants are operational worldwide. To overcome the energy prospectus of these plants, utilizing solar energy to meet the energy demands is a viable option. The conversion of dinitrogen to nitrogen-based compounds, which may then be used to fertilize plants, can be powered by the sun. Sun fertilizers refer to those

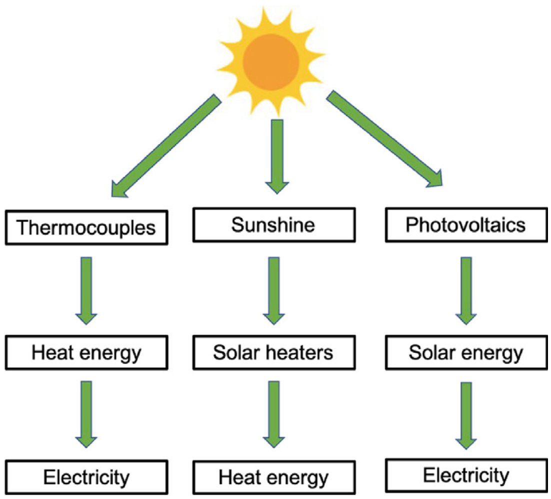

Fig. 2. Solar energy utilization in various ways.
Source: Adopted from Liaqat (1990).

made from plants that utilize solar energy. Solar fertilization generation is solely based on solar power, nitrogen, and water from the air to obtain nitrogen-based fertilizers. According to a study carried out in 2018, 250 pet joules of energy/per year can be saved just by decreasing 10% the usage of urea or ammonia-based fertilizers (Raza et al., 2020).

4.1.11. Solar-powered agricultural robots

Solar-powered agricultural robots offer enormous potential for establishing agriculture chores such as sowing, weeding, ploughing, spraying, and harvesting food in greenhouses and open-field farms (Samuel and Beera, 2013). Agriculture robots are now powered by rechargeable batteries and electric motors, so combining a PV module with them is a viable solution (Olosunde et al., 2009). Several firms are doing development and research initiatives to create smart weeding robots that use digital cameras to distinguish crop rows and gather large-scale field views using image processing methods that are compatible with agricultural procedures. As a result, such robots may offer the potential to present sustainable solutions and lower the cost of agricultural operations (Balasuadhakar et al., 2016).

4.2. Wind energy

The wind is classified as the flow of air from a high-pressure region to a low-pressure region as depicted in Fig. 2. Wind power differs from solar power in the sense that it is daily available for 24 h. Wind power-oriented technologies can be used to generate both electrical and mechanical energy. Wind-focused technologies are considered the wildest growing renewable-energy technology by crossing bio-based power. Enhancement in renewable energy technologies will encourage farmers to invest in wind energy infrastructure to reduce the cost of wind energy generation leading to self-reliance. Using wind energy is not only reliable but cost-effective for providing power to farmlands for various purposes. Water pumps for irrigation can be operated by wind turbines and thereby, eradicating the need and cost of installing electrical equipment such as transformers, electric lines and poles (Hasan et al., 2019a,b) (see Fig. 6).

Due to the high capital investment in the wind sector policymakers and investors are inclined towards developing alternatives to minimize the difference between cost and benefits (Hanif et al., 2019). Satisfying the economic prospects of the investor is one of the major steps in the overall project which can be met by selecting a suitable location (Amjad et al., 2018). Selecting efficient and economically feasible locations for wind power generation is a costly procedure dependent upon various factors (Ramos et al., 2003). As economic, environmental, and social aspects, the wind potential of the region must be considered. The efficient performance of a renewable source system is directly attributed to the features of the region including economic activities, distance from the road, local resources, energy infrastructure, and residence infrastructure, transportation network improvements may boost agricultural and aggregate production in developed countries. (Adamopoulos, 2011; Ajiboye and Afolayan, 2009). Selecting a location for installing wind turbines is considered a comprehensive analysis of various factors (Sipahioglu and Barringer, 2003). From the literature we can see observe which 10 factors are most important in terms of a plant's efficiency as they affect it directly, these factors are depicted in Fig. 3. It is to be noted that these factors are important as they are choices regarding the utilization of variables, weighted, and used in the decision-making models which consider the characteristics and specifics of a selected location (see Fig. 7).

Since wind energy does not require fuel or diesel to operate, so it is considered environmentally friendly leading to a reduction in noise pollution. This results in less emission of harmful gases such as GHGs (Zhang et al., 2018). Having wind-powered farms favor the reduction of operation and maintenance costs along with the economic benefit of reducing the amount of imported fuel required to run a farm (Diaconu et al., 2011). A farm's power requirements vary from 400 W to 40 kW which can be fulfilled by small wind turbines (Ghafoor et al., 2016). Hence, farm and ranch owners can generate wind power using a small area of their land. Farmers and ranchers will benefit immensely from net metering by using their farms and ranches respectively (Sheikh, 2010).

Wind energy can be utilized for various applications which include direct water pumping for agricultural practices. When the pump is operated directly using wind via a wind rotor it can be categorized as direct water pumping. Through this system simple energy transformation can take place; from kinetic energy (wind) to mechanical energy to hydraulic energy for pumping water. This method has a major disadvantage in terms of the pressure of the water supply which can be restricted by the water tank or the reservoir. As a result of low hydrostatic pressure, various applications are not practical via direct water pumping. Recently, manufacturers have moved from outdated wind technologies to electric pumps powered by wind. Windmill pumps and wind electric pumps are differentiated regarding the location of the power source (wind generators) and water source, as they can be at separate locations. This will enhance the efficiency of the system as wind generators can be installed at locations where wind availability is favorable.

Irrigation by means of the wind, using agriculture-compatible poly-winged turbines that can suck water from deep soil, wind energy in agricultural irrigation may boost plant production and reduce energy expenditures. High-income countries like Turkey, which will have 3500 wind turbines with an installed capacity of over 7600 MW by 2019, are major users of such systems. Farmland is a viable location for wind turbines because of the little damage they do to crops. It is possible to use low-speed and high-speed turbines, which is a modern method that makes less noise (Otanicar et al., 2012). Farmers' revenues can be boosted as a result of energy and agricultural co-production.

Wind electric pumping or solar PV systems are normally better suited for farming small lands (<2 ha) that are remote and off-grid. Large-scale cost competitive irrigation can be achieved by integrating PV arrays with wind turbines. The irrigation system can be segregated into winter and summer crops. Extra power

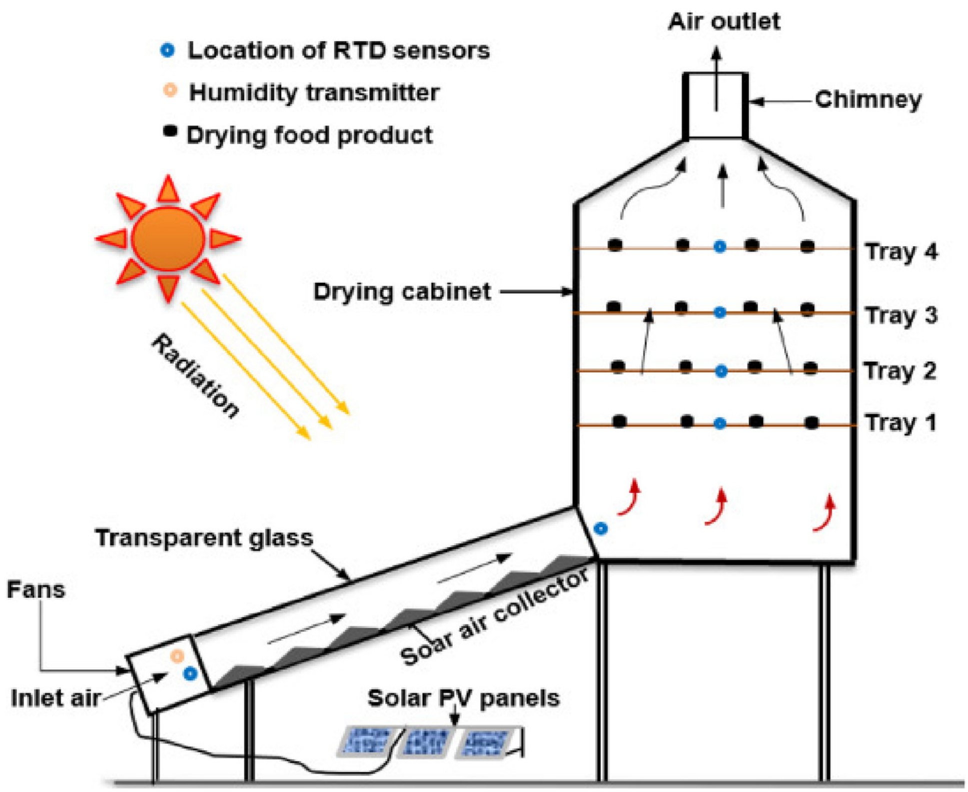

Fig. 3. An experimental study by Gilago and Chandramohan (2022) to evaluate performance of natural and forced convection indirect type solar dryers during drying of ivy gourd.

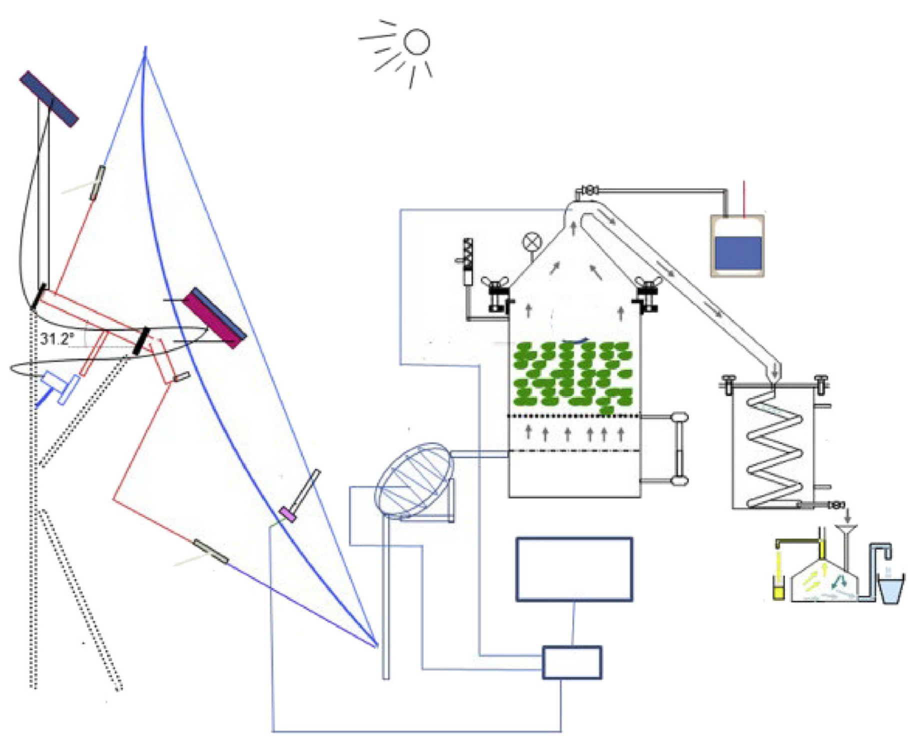

Fig. 4. Schematic of solar distillation system. Reprint with permission of (Development of hybrid solar distillation system for essential oil extraction) (Afzal et al., 2017).

generated from the integrated system can be utilized for various on-farm purposes enhancing the overall profitability of the system (Wang et al., 2017). The integrated system can be used concurrently for safety and to enhance pumping capability. The prospect of energy available throughout the year is an advantage for crop growth in various countries. Such integrated systems for

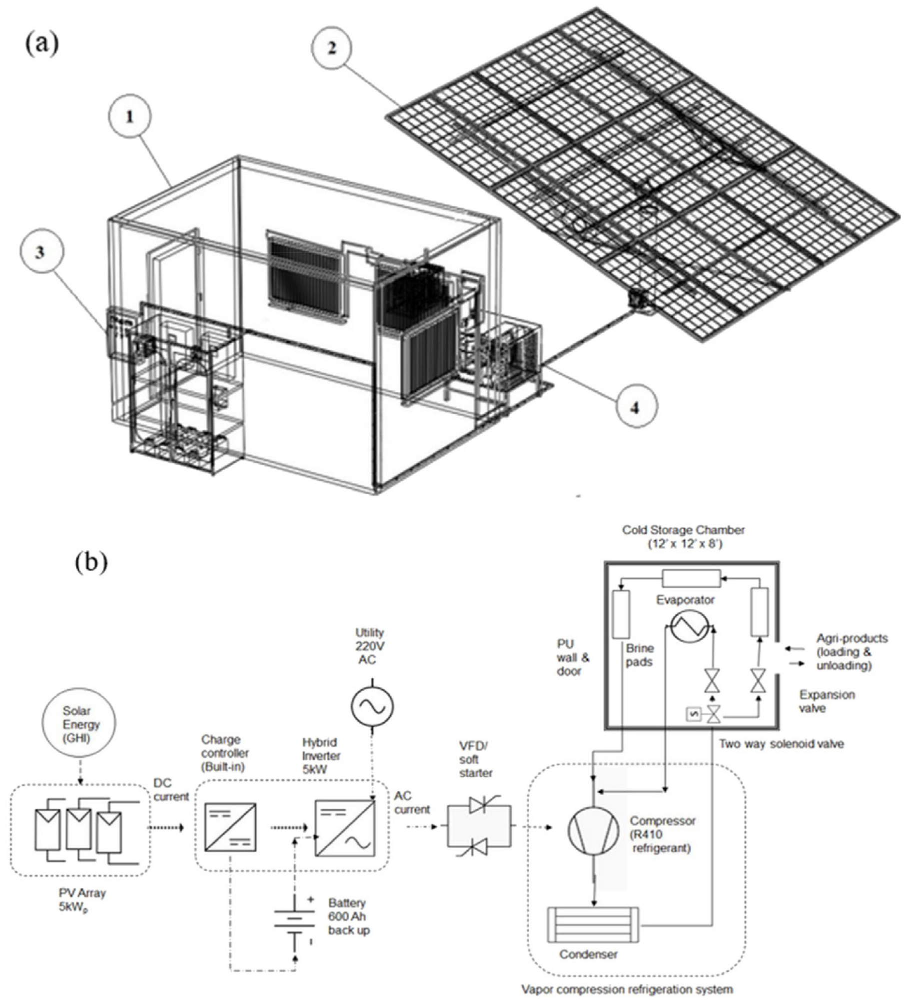

Fig. 5. Solar-hybrid cold energy storage system coupled with cooling pads backup (Munir et al., 2021).

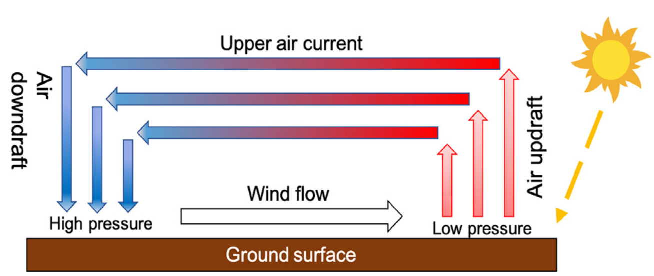

Fig. 6. Schematic diagram of wind flow.
Source: Adopted from Hasan et al. (2019a,b).

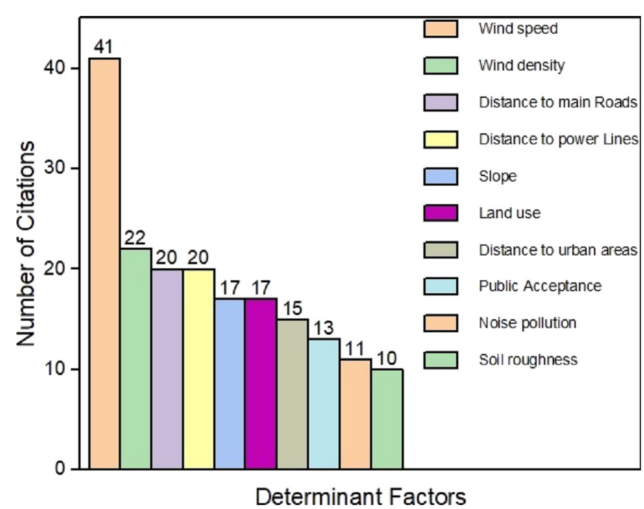

Fig. 7. Wind factors cited in the literature regarding site selection.
Source: Adopted from Ali et al. (2002).

irrigation and drainage purposes can be devised for large-scale purposes. All equipment on farming lands can be operated using scaled-up integrated systems.

In the US, wind farms are usually installed in agricultural lands located in the Midwest, through the effect of microclimate wind turbines may potentially affect crop growth (Bundschuh et al., 2017a,b; Comer et al., 2019; Munir et al., 2021; Reimert et al., 2000; Singh et al., 2018; Sutar and Butale, 2020). There is no such significant evidence of the effects of wind farms, whereas, some studies have reported a mitigating effect (Arıand Gencer, 2020; Kabak and Taşkinöz, 2020). According to the literature, there are three main hurdles, first, carbon dioxide, heat fluctuations, and changes in moisture, caused by large wind turbines may affect the crop both positively and negatively depending on weather parameters. Studies by CWEX depict that plant respiration may increase during night-time due to the warming effect whereas, the changes in water and carbon dioxide may attribute towards photosynthesis and transpiration during daytime. The second issue deals with climate change as a result of wind turbines. This depends on various complicated and specific factors, not to account for interactions between crop surface and turbine features (Mentis et al., 2016; Rediske et al., 2019). The third issue deals with local ecosystems and productivity either from direct or indirect effects of microclimate, soil erosion, noise and visual pollution, bird or bat flight path impedance or disturbance, and pathways for tractors (Kondili and Kaldellis, 2012; Leung and Yang, 2012; Rediske et al., 2021; Rehman et al., 2019). According to a study carried out in 2016, there is a 14% enhancement of output energy from a wind farm when the crop underneath it is changed from corn to soybeans (Ali et al., 2012).

Farmlands can be utilized for multidimensional applications such as energy production and food. Solar and wind energy can be generated along with agricultural products using the same land. This can be a win-win combination, by generating electricity, a stable and long-term source of income for the farmers. According to a study conducted by the DOE, in the USA 80,000 jobs for the agricultural sector can be generated alone from wind energy along with USD 1.2 billion in income for farmers (Poullikkas et al., 2013).

Although wind energy has benefits it also has drawbacks as discussed above. Today, applications using wind power for agricultural purposes are of reduced significance whereas, previously wind power was used for pumping groundwater. However, the maintenance and mechanical sensitivity of windmills, make conventional fuel, and if possible solar pumping a better option.

4.3. Biomass energy

Various renewable energies are considered due to the diversity in origin and availability of conversion technologies for energy-based products (Adkins and Sescu, 2018; Vick and Almas, 2010), among which biomass is an option with potential use for providing energy. Biomass includes various plants produced via photosynthesis and their by-products (Armstrong et al., 2014). Bioenergy is a crucial part of the overall energy economy, having a share of 9.5% of the total primary energy and around 70% share of the total renewable usage today (Baidya Roy and Traiteur, 2010). This bioenergy is not only utilized for domestic purposes involving heating and cooking but also consumed by various small industries (i.e., brick and charcoal kilns).

Bioenergy is an essential energy source that can fulfill the agri-food sector and beyond demands for heat, power, and transportation fuels (Harris et al., 2014; Sanz Rodrigo et al., 2017). Agri-food biomass byproducts can be utilized to provide energy for processing, storage, and cooking (Xia et al., 2016).

Transforming crops to obtain energy has gained global attention with the upsurge in prices of conventional fossil fuels. Using biomass from crops, including grain and plant parts, as raw material for bioenergy generation may strive with food supplies and also may eradicate crucial parts of plants that help in sustaining the productivity and structure of the soil. Agricultural-based research can play a role in mitigating these trade-offs by improving specific biomass traits of dual-purpose crops. For marginal land, new crops can be developed where competition with food crops is less. Sustainable livestock practices which are less dependent on crop residues can also contribute to mitigating these trade-offs. Thresholds limits of crop residues will have to be defined by agronomists to obtain sustainable production in low-yield rainfed systems including residues utilized for biofuel production. Research based on agriculture can facilitate the enhancement of the energy efficiency of crops, resulting in value addition as a renewable resource having low net carbon emissions.

Biofuels presently are sucrose or starch-based ethanol derived from biomass. Ethanol having a high-octane number can be mixed with gasoline in small proportions for direct usage in internal combustion engines. These engines can be used to perform various farming-related tasks such as ploughing, irrigation, and machine operation.

4.4. Geothermal energy

Geothermal energy is a non-carbon native environmentally friendly renewable-energy resource contained in the interior earth (Tang et al., 2017; Zhou et al., 2012), it is normally attributed to volcanic and tectonic activity beneath the surface of the earth. The heat used in the geothermal process is normally stored in rocks found at depths of the earth's surface (Xia and Zhou, 2017), and also in hydrothermal reservoirs at elevated temperatures (Rajewski et al., 2014). Many researchers concur in terms that geothermal energy is a renewable resource of energy (Rajewski et al., 2016; Zerrahn, 2017). It may be noted that the rate of extracting heat from geothermal reservoirs is normally faster than replenishing the used heat which is dependent on the geothermal applications, geological time scale and the method adopted to reinject heat (Moravec et al., 2018).

Brine solution has been identified as a medium for heat used for steam generation. Geochemistry researchers have categorized thermo-fluids into two types: mineral-laden hot water termed 'brine' and steam (Dai et al., 2015). These types of fluids facilitate in transporting of heat from underground to the surface, for both electricity generation and direct applications, via drilled wells connecting to the geothermal reservoirs. The depth of geothermal reservoirs may vary from 300 meters to 3000 meters where the liquids may be confined in various hydrothermal porous hot rocks and geothermal reservoirs (Aydoğdu et al., 2021). Depending on the characteristics of the reservoirs, pumping or free-flow methods can be applied for extracting hot native fluids. To optimally utilize the extracted heat, various heat management techniques for geothermal fluids may be adopted (Bundschuh et al., 2017a,b; Riaz et al., 2018). In the end, power conversion systems may be employed to convert the geothermal heat to electricity or for direct heating applications (Bioenergy, 2017; Jankovsky et al., 2021; McKendry, 2002a,b; Vidal and Hora, 2011).

Renewable sources of energy count for almost 28% of the world's energy generation capacity (DiPippo, 2015). Among these sources, geothermal energy is considered reliable due to its non-dependency on the season, climate, and geographical conditions (Milora and Tester, 1976). According to a study, the installed capacity of geothermal energy in 2020 was estimated to be around 20 GW with 90% of the output energy being contributed by 8 countries namely Iceland, Philippines, New Zealand, Indonesia, Italy, Mexico, Japan, and United States (Axelsson, 2016; Chen and Jiang, 2015). Growth forecasts suggest that by 2050, geothermal energy will contribute to around 3% of the electricity generation and 5% of the hat load globally, leading to the removal of more than 1 billion tons of CO_2 in 2050. To make this forecast a reality, well-disciplined efforts to address various concerns regarding social, economic, management, social, environmental, and political challenges will have to be made.

Geothermal energy can be utilized in the sector of agriculture by controlling the required temperature for optimal plant growth both in greenhouses and open fields. In open fields, geothermal water can be deployed for soil heating and for irrigation where easy access to water sources is not available. Soil heating can be achieved by laying out thin pipelines circulated with warm fluids. The greatest drawback to this method is the economics, and this proves to be feasible in very few cases. Soil heating with buried pipelines without an irrigation system can result in decreasing heat conductivity of the soil due to the decrease in humidity and thermal insulation surrounding the pipes. Therefore, the optimum solution revolves around combined irrigation and soil heating (Yang and Yeh, 2009) if geothermal waters are to be used directly then their chemical composition has to be monitored closely to avoid negative impacts on plant growth. Open field temperature control mitigates adverse effects resulting from low environmental temperatures, leading to an extended growing season and a rise in plant growth. This also sterilizes the soil increasing productivity.

In many countries, geothermal energy in agriculture is most commonly used for greenhouse heating. Advantages of greenhouse heating include an extension of cultivating time for out-of-season vegetables and flowers. Different methods are available to achieve feasible plant growth dependent on optimum conditions such as the quantity of light, temperature, CO_2 concentration, airflow, and humidity of the soil and within the greenhouse. Heating of greenhouses can be achieved by circulating hot water via pipes or ducts in or on the floor, forced air flow in heat exchangers, and also with the help of finned units placed on walls or beneath benches. The cost of operating a greenhouse accounts for 35% of product (i.e., vegetables, fruits, tree seedlings, and indoor plants) costs, which can be reduced significantly by using geothermal heat. This case is true when the flow of geothermal fluids takes place naturally. Pipes, heat exchangers, and pumps may require maintenance regularly as geothermal fluids tend to leave deposits due to their chemical composition. As a result of implementing geothermal technology, the Netherlands has seen a major increase in tomato production.

5. Conclusions

By exploring renewable energy resources such as solar, biomass, wind, and geothermal energy, the paper has identified the abundant availability of these sources in agriculture. It has discussed the benefits, challenges, and opportunities associated with the adoption of renewable energy technologies in the agricultural sector. Transitioning to alternative energy sources for energy management in agriculture holds great promise for reducing greenhouse gas emissions, improving energy efficiency, and promoting sustainability in food production. However, achieving these goals requires concerted efforts to address challenges and barriers while embracing renewable energy technologies and practices. By advancing energy management practices and promoting the adoption of renewable energy in agriculture, we can contribute to a more sustainable and resilient agricultural sector, ensuring food security, mitigating climate change, and fostering overall sustainable development. Identifying renewable energy sources to replace today's dwindling supply of cheap and usable fossil fuel is the only practical response to the problem of depleting non-renewable resources. For the foreseeable future, solar energy is the only source of completely renewable energy. Sustainable solar energy may be generated via a variety of means, including wind turbines, hydroelectric dams, solar thermal collectors, and photovoltaic cells. Throughout the review, various benefits of renewable energy adoption in agriculture were discussed. These include reduced dependence on fossil fuels, cost savings through improved energy efficiency, increased energy security, and enhanced environmental sustainability. Moreover, the integration of renewable energy systems in agriculture can contribute to the resilience and self-sufficiency of rural communities, especially in developing countries where energy infrastructure is limited. Integrating renewable energy into existing agricultural techniques, particularly manual ones, requires additional capacity development (for example, to maintain drip irrigation systems) as well as marketing and access markets for new items and increased yields for present products. Connecting renewable energy supply to appliances requires investments in innovation that test and implement technology solutions matched to the demands of different agri-value chains. In order to make the technological solution more affordable, it is important to place greater emphasis on energy efficiency in home appliances.

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CRediT authorship contribution statement

Yaqoob Majeed: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Muhammad Usman Khan:** Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization. **Muhammad Waseem:** Methodology, Software, Formal analysis, Data curation, Writing – review & editing, Visualization. **Umair Zahid:** Data curation, Writing – review & editing, Visualization. **Faisal Mahmood:** Validation, Writing – review & editing, Supervision, Project administration. **Faizan Majeed:** Conceptualization, Validation, Resources, Writing – review & editing, Project administration, Funding acquisition. **Muhammad Sultan:** Writing – review & editing, Data curation, Visualization, Supervision. **Ali Raza:** Writing – review & editing, Data curation, Visualization, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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