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Innovative Approaches to Sustainable Agriculture: Ensuring Food Security and Environmental Health

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ABSTRACT

Sustainable agriculture has become vital for supplying the world's increasing demand for food in the future. While ensuring food supply, this technique addresses decreased biodiversity, loss of resources, and global warming. Some practices like Crop Rotation, Integrated Pest Control, and Precision Land and Water Management increase yields while preserving the environment and other resources. Precision farming and remote sensing improve soil health and crop production. Cover crops, organic farming, and efficient irrigation improve soil and save water. Sustainable agriculture requires teamwork to reach its potential. To secure food security for future generations, governments, researchers, and stakeholders must support these practices.

Keywords: *Sustainable agriculture, Food Security, Environmental Health, Precision Agriculture*

INTRODUCTION

Sustainable agriculture is essential to life on earth and, by extension, to all humanity's endeavors, since it can consistently provide resources such as food and water to a rising global population (Beus & Dunlap, 1990). Many factors, including a rapid loss of biodiversity (Peters, 2010), land degradation (Rhodes, 2014), salinization of soil (Singh, 2020), climate change (De Wrachien et al., 2021), depletion of water resources (Abd-Elaty et al., 2022), increasing expenses of production (Pu & Zhong, 2020), a constant decrease in the number of farms, and associated poverty and a decline in the rural population pose a threat to agriculture's ability to meet human needs both now and in the future (Rivera-Ferre et al., 2013). Major technical breakthroughs have been applied throughout much of human history to boost agricultural productivity with limited resources. By 2050, there will be 9 billion people on the planet, an approximate 25% increase over the present population (DeSA, 2015).

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But there will be a greater increase in population, mostly in developing nations like China, Mexico, India, and others (McNabb & McNabb, 2019). By 2050, food production should have doubled to fulfill future food needs (X. Zhang & Davidson, 2018). To fulfill the world's food demand by 2050, it is specifically recommended that grain crops and meat output be expanded from 2.1 billion to 3 billion tons, and from 200 million to 470 million tons, respectively (Tripathi et al., 2019).

Sustainable agriculture aims to conserve biodiversity, improve soil composition, and cultivate a range of crops without the use of artificial fertilizers or pesticides (Shrestha et al., 2021). In conventional agriculture, artificial fertilizers and insecticides are frequently used to increase the output of a certain genetically engineered crop or group of crops (Yang et al., 2024). This method degrades the landscape ecosystem and uses a large amount of chemicals and energy. (Shrestha et al., 2021). A strategy for boosting output on already cultivated land while reducing adverse social and environmental effects is called sustainable intensification. Sustainable intensification is managing agricultural land's environment and productivity better at the same time (Buckwell et al., 2014). Sustainable agricultural intensification aims to improve food production on the same land area while lowering negative environmental consequences and bringing about positive social, economic, and environmental outcomes (Shrestha et al., 2021).

Agriculture that is sustainable is advantageous both for the environment and human health (Horrigan et al., 2002) while Natural fertilizers like manure and ground cover are examples of sustainable methods that are typically not used in conventional agriculture. Chemical pesticides and fertilizers are sprayed on the crops in this type of farming. These dangerous compounds have the ability to contaminate crops, animals, and people. Eating these foods puts people's health at risk (Shrestha et al., 2021). Enhancing soil health (Reganold & Wachter, 2016) and increasing crop yields (Ponisio et al., 2015) are two advantages of implementing sustainable agriculture methods, as reported by several researchers. For instance, according to research by (Pretty et al., 2006) the implementation of sustainable agriculture techniques increased yields on 286 projects in 57 developing nations by an average of 79%, indicating the practices' potential to raise productivity and improve food security. Sustainable agriculture, as opposed to conventional agriculture, prioritizes long-term feasibility, resource conservation, protection of the environment, and sustainability in terms of society (Dönmez et al., 2024). According to (Chizari et al., 1998) this change entails switching from conventional farming to techniques that rely more on organic materials, minimize chemical inputs, and safeguard natural resources. (Brodt et al., 2006) emphasizes that sustainable agriculture is a labor-intensive, information-rich, and management-intensive enterprise. This strategy protects farmers' financial stability while also reducing environmental damage Sustainable agriculture is characterized by its all-encompassing agricultural practices and aims to fulfill current demands without sacrificing the ability of subsequent generations to fulfill their own. It distinguishes itself from conventional agricultural practices by promoting the values of social justice, financial sustainability, and environmental protection. Its dedication to the long-term preservation of resources highlights its distinct approach to agriculture (Dönmez et al., 2024).

Precision farming and remote sensing, two recent developments in agricultural technology, have created new avenues for improving sustainable farming methods and their effects on crop yields and soil health (N. Zhang et al., 2002). For example, (Schut et al., 2018) showed that improving agricultural produce and minimizing environmental effects might be achieved by combining precision agriculture technology with sustainable methods like variable-rate irrigation and site-specific nitrogen management. In a similar vein, farmers may now make better judgments regarding the management of their agroecosystems by using remote sensing technologies to track markers of soil health (Iost Filho et al., 2020). Sustainable agricultural methods will be more crucial to ensuring food availability and environmental sustainability as the global population increases and food demand rises (Godfray et al., 2010). To maximize the benefits of sustainable agriculture techniques on crop yields and soil health, governments, researchers, and other stakeholders must collaborate and fund additional studies (Garnett et al., 2013).

Essential Practices in the Sustainable Farmer's Toolkit:

Soil Health:

Healthy soil is defined as "the capacity of soil to function as a vital living system within ecosystem and land use boundaries to sustain plant and animal production, maintain or enhance water and air quality, and promote plant and animal health" (Doran & Zeiss, 2000). The majority of living things derive their mineral nutrients from the earth, which is their primary source. Proper soil management guarantees that the right mineral components reach the food chain and do not become poisonous or insufficient for plants (White et al., 2012).

Soil organic matter is crucial for integrating several soil health factors. There are two types of soil organic matter: labile and stable pools. Each kind of soil organic matter has unique properties and purposes. Depending on the soil type, temperature, and management techniques, the proportion of organic materials in soil used for agriculture (Usharani et al., 2019).

Organic agriculture is the most feasible method of farming and is gaining popularity worldwide due to its ability to enhance soil nutrient cycling, microbial operation profusion and variety, groundwater purity (reduced nitrate levels) (Gong et al., 2011), harvest quantity and quality as demonstrated by the production of wheat, potatoes, watermelon, and strawberries (Schrama et al., 2018). Leguminous crops, such as alfalfa and Sesbania spp., are commonly utilized in organic agriculture and have been shown to enhance organic components of soil by approximately 50% (in comparison to mineral fertilizer); after 13 weeks, Sesbania rostrata produces 16.8 tons per ha dry mass. They also boost soil N supply capability (Gong et al., 2011), (Matoh et al., 1992). A 12-year research on rice and maize crops found that organic systems that employed manure and dung sources had higher populations of microbes and enzyme production than conventional systems (Chang et al., 2014).

Organic agriculture may catch more than traditional agriculture following a decade to thirteen years of cropping, although producing lower yields than conventional farming (Schrama et al., 2018). Organic farming is generally the best way to improve the soil and fruit standards that grow in it, but if yield is your primary priority, it might not be the best option for farmers in the short term (Leskovar & Othman, 2018). As a result, there may eventually be a productivity difference between sustainable and traditional methods, and sustained organic farming may improve the stability of Soil operations and microbial colonies (Schrama et al., 2018). However, organic agriculture can accomplish agricultural sustainability and is good for the ecosystem and human well-being (Gamage et al., 2023).

Cover Crops:

One strategy to improve soil quality and production is to plant cover crops, or crops that are grown to protect and enrich the soil. Cover crops can affect biological characteristics like nitrogen mineralization, enzymatic tests (such as beta-glucosidase and phenol oxidase enzymatic actions), and biomass of carbon and nitrogen microbes. They can also affect soil physical characteristics like soil particle cohesion and water availability. Although these impacts are not always constant, planting cover crops can change the availability of nitrogen (Mbuthia et al., 2015) in the soil and raise the concentrations of organic carbon (Blanco-Canqui et al.). Specifically, using cover crops for decades can lead to a considerable rise in organic carbon concentrations (Poeplau & Don, 2015). In addition to decreasing soil erosion, surface drainage, and underground release of nutrients, cover crops may also raise infiltration rates. Apart from reducing soil deterioration (Olson et al., 2014), surface runoff (Jian et al., 2020), and subsurface nutrient leaching (Norberg & Aronsson, 2020), cover crops can also raise penetration rates(Stewart et al., 2018).

Crop Rotation:

Experts are growing more worried these days about the depletion of soil brought on by intensive farming (Khaledian et al., 2017). Approximately 60% of soil degradation during the 1950s has been linked to varying levels of soil biological activity, with cultivation techniques emerging as a significant driver (Lal, 2015). Researchers want to make a substantial contribution to the worldwide adaptability of agricultural goals by transforming research findings about soils into practical methods that improve farmers' comprehension of the profitability of their agricultural operations (Doran, 2002). Crop rotation is the practice of planting various crops in a certain sequence on a given piece of land in order to preserve soil health and yield over time. It is one way of environmentally friendly agricultural operation that tries to enhance soil biomass and prevent erosion of topsoil (Folnovic, 2021). Crop rotation prevents insects and diseases from reproducing, which disrupts their life span. Restoring plant nutrition and lowering the need for artificial fertilizers are two benefits of crop rotation that incorporate certain plant varieties (Shrestha et al., 2021). Crop rotation is one useful technique in the implementation of environmentally friendly agriculture. Diversified crop rotations (DCR) are rotations consisting of three or more crops, as opposed to monocultures or double-farmed rotations (Wang et al., 2020).

Water Management:

Currently, 71% of water reserves are used for agriculture, mostly for water application. The majority of irrigated land was initially established in the 20th century, even though it has been used for thousands of years (Gomiero et al., 2011). As irrigated agriculture grows, it is anticipated that water for irrigation will become increasingly scarce. For irrigation to continue, water needs to be available at all times (D'Odorico et al., 2017). A major objective of irrigation development is water conservation, particularly in areas with limited water resources. "Better management" means increasing the effectiveness of irrigation and/or water allocation. The latter is significantly affected by irrigation methods, water application settings, and timing (Harwood, 2020).

The goal of water sustainability in agriculture is to achieve an equilibrium between supply and demand for water with respect to quality, amount, location, cost, duration, and ecological impact. Since irrigation technique controls how often plants are irrigated, timing and irrigation technology are closely intertwined (Falkenmark, 2013). To address problems with declining soil quality and soil moisture deficits, people in the region of the Nile have been developing Barrier-based soil and water conservation on slopes strategies over the last 7000 years that are specific to their agricultural operations (Roose, 2008).

Planning of Irrigation Water:

Choosing the right time and amount of water to provide crops is known as irrigation scheduling. Promoting agricultural sustainability while preserving water and enhancing the effectiveness and lifespan of irrigation systems is necessary (Alshamary & Noori, 2024). The ideal times to irrigate, the intricacies of the amount of water in the soil, and the right volume of water to employ all need research. When to irrigate also depends on how well the irrigation technique works (Nazari et al., 2018). There are several effective methods and strategies for scheduling irrigation. There are several methods for determining irrigation timing and depth parameters based on soil water measurements, expected soil water balances, and signals of plant stress. These methods can involve the use of simple rules or more complex algorithms. Many of them require improvement or additional research before they may be used in real-world situations (Lalehzari et al., 2016). If there is a shortage of water for other users or applications, irrigation planning becomes even more crucial in places with limited water resources than in those with enough of it (Dhawan, 2017).

Deficit Irrigation Practices:

Stage-based deficit irrigation is characterized by the application of RDI at various phases of plant development, with less water applied during non-essential growth stages and enough water applied during key growth stages to fulfill full plant evapotranspiration (ET) (Chai et al., 2016). Previously, crop irrigation needs were determined without considering water supply limits. Based on the crop's overall water requirements, an irrigation schedule was then created. Nevertheless, the quantity of water available for agriculture is decreased in dry and semiarid areas due to expanding urban and industrial water demands. For the best yields, water is therefore frequently insufficient. It is necessary to install irrigation systems that are independent of the crop's overall water requirements to use water more effectively and economically. Deficit watering, subsurface irrigation, and partial root drying are all part of this technique (Hashem et al., 2018).

Drip Irrigation:

Drip irrigation is the practice of supplying water to plants' roots drop by drop. Fertigation and drip irrigation together may increase output by as much as 200% and 133% in sugarcane, respectively. When it comes to water conservation, it may save as much as 50% more than Floodplain and row irrigation. Moreover, flooding is 30% less successful than drip fertigation. In addition to saving energy, drip irrigation reduces the frequency and spread of pests and diseases and stops weed development (Manda et al., 2021). Hydroponics is an option if our soil is not so good. If our climate isn't ideal, we can use net homes or greenhouses. However, we are unable to cultivate anything without water. The best way to hydrate plants is using drip irrigation (González-Cebollada, 2015). Drip irrigation is forty percent more productive than conventional irrigation methods since it uses 40% less water. Fertilizer consumption may also be reduced by this strategy (Smith et al., 2016). It makes it possible to evenly provide the necessary amount of water to every plant at once. In addition to preventing soil erosion and weed growth, it makes saline irrigation possible (Arshad, 2020).

Soil Moisture Sensors:

Farmers may determine the ideal irrigation time and amount for plant growth by using soil moisture sensors, which measure the amount of water in the soil (Yin et al., 2021). Three main components of a soil moisture sensor are typically the transmission circuits (such as coaxial cables), the electronics or instruments for signal processing, and the probe electrodes placed in the soil to provide bias and readout. These days, soil moisture sensors measure variations in soil parameters including mass, soil water content, soil potential, and dielectric permittivity to determine the quantity of water available (SU et al., 2014).

In recent years, significant progress has been achieved in portable moisture monitoring for innovative farming (Bogena et al., 2022). The primary barriers to the adoption of portable moisture sensing are the expense of the equipment and the inability to supply energy to the instruments and information transfer apparatus remotely. Volume production and additional optimization will enable the former. As wireless power transfer (WPT) advances significantly, the latter will soon be possible. WPT is a method of transferring electricity from an energy source to a remote electrical appliance via soil or an air gap. WPT has a lengthy history of use. Through the Tesla coil experiment in 1899, The technique of sending electricity without wires was created by Nikola Tesla. Many WPT techniques have been created and have advanced significantly since Tesla's groundbreaking breakthrough (Le et al., 2023). The correct installation and positioning of the monitoring system are essential to its efficacy. The placement of the sensors or samples should reflect the field, garden, or landscape as a whole. Steer clear of positioning sensors at the summit of a hill or the base of a dip (Hunduma & Kebede, 2020).

Pest Management

Pesticides are substances, either synthetic or biological, that are applied to crops to protect them from pests (such as rodents, insects, or undesired plants) and pathogens (microorganisms, such as bacteria, viruses, fungi, or other agents). Their use has also grown significantly during the past few decades (Mahmood et al., 2016). Pesticides are widely utilized across the globe not just in farming contexts but also to prevent bug infestations (Hossain et al., 2017). Throughout 1990–2022, the use of pesticides in Asia remained at 1.17 kg per hectare annually (Mahmood et al., 2016). They are used to clear dwellings of dangerous pests like ticks, cockroaches, fleas, and mosquitoes. Grass and other undesirable vegetation are controlled with the application of herbicides (Sherwani et al., 2015). Nevertheless, a variety of insects are managed with the application of insecticides (Iqbal et al., 2021). Disinfectants are useful in controlling the spread of pathogens, and toxic chemicals can be used to eradicate rodents and rats (Rani et al., 2021).

In an attempt to safeguard plantations and increase agricultural output, emerging nations are reportedly using antiquated, more hazardous, non-potent pesticides with the intention of growing their economy (Rani et al., 2021). A national epidemiological profile of pesticide toxicity was assessed between 2006 and 2015, during which time 11,087 cases of pesticide poisoning were reported. Throughout the period of 10 years, there was a rise in pesticide-related illnesses. Pesticide poisoning is a major public health issue in Malaysia, where there are 3.8 cases for every 100,000 people (Bachmann, 2018); (Kamaruzaman et al., 2020). In India, poisoning with aluminum phosphide also resulted in fatalities (Parmar et al., 2015). An analysis of 4148 pesticide-poisoned patients' medical records conducted in Nepal between April 2017 and February 2020 revealed that the most common type of poisoning (95.8%) was self-poisoning (Ghimire et al., 2022).

Integrated Pest Management:

The sustainable approach to managing pests known as integrated pest management, or IPM, has been around for a while. While the term "integrated pest management" (IPM) has been defined differently, previous IPM models emphasized the environmental and, to a lower degree, adaptive elements of pest control (Peterson et al., 2018). (Stenberg, 2017) introduced a new IPM pyramid that indicates the absence of a comprehensive IPM plan utilizing both traditional and modern methodologies. The new Integrated Pest Management (IPM) model is divided into four main sections that address various pest management techniques, grower knowledge and resources to address the pest problem, arranging and preparing insights to make necessary decisions, and maintaining open lines of communication for learning about pests and ways to manage them. The concept of pest prevention has changed over time to become pest management because it is now recognized that, aside from recently introduced invasive pests, an integrated strategy for controlling insect populations to thresholds that avoid revenue losses is better for eliminating or reducing them for both ecological and financial objectives (S. K. Dara, 2019).

Using cultivars that are both pest-resistant and pest-tolerant (Douglas, 2018) that have been created via conventional breeding or genetic engineering is known as "host plant resistance” (Nelson et al., 2018). Certain varieties have physiological, structural, or metabolic traits that make the plant less appealing to pests or less suitable for their feeding, growth, or reproduction. These varieties minimize crop losses by withstanding or resisting insect attacks. (S. K. Dara, 2019).

Cultural control is the use of effective agricultural methods to minimize or stop damage from pests. Selecting clean plant material or seed is essential to reducing the likelihood of introducing pests at the start of crop development. Changing the planting date can help prevent pest infestations or steer clear of the most vulnerable stages. In Uganda, early cowpea planting decreased infestations of aphids, thrips, and pod bugs (Karungi et al., 2000).

Natural enemies that can effectively reduce pest populations under certain circumstances include parasitic wasps and predatory arthropods (Hajek & Eilenberg, 2018). Conventional methods for controlling endemic pests include introducing naturally occurring predators on a regular basis, protecting their populations using refuges, and avoiding acts that threaten them. Biological management has been effective in greenhouses (Gotyal et al., 2022) and specialist crops like field-grown strawberries (Dwiastuti et al., 2021).

The employment of a range of passive methods for pest population suppression, trapping (which is sometimes comparable to behavioral control), removal, or destruction is referred to as physical or mechanical control (Gamliel, 2017). Physical or mechanical methods of controlling pests include using row covers or netting to exclude them, vacuuming or hand-picking weeds, using mechanical tools to control weeds, setting up rodent pest traps, changing the temperature or humidity in greenhouses, steam sterilizing or solarizing, and using reflective materials or sound devices as physical or visual deterrents for birds (S. S. Dara et al., 2018; Gogo et al., 2014).

Microbial control typically involves the use of entomopathogenic bacteria (Deka et al., 2021), fungi (Mann & Davis, 2021), microsporidia (Kňazovická et al., 2022), nematodes (Danishiar et al., 2023), or viruses (Deka et al., 2021). Additionally, it entails using certain bacteria' fermented outputs as a defense against plant parasitic worms, insect pests, and plant diseases (Lacey, 2017).

The use of artificial chemical pesticides is commonly known as chemical control (S. S. Dara et al., 2018). However, manmade chemicals as well as those derived from microbes or plants should be included in chemical control in order to be technically correct (Abubakar et al., 2020). While microbe-derived toxic metabolites such as bacillus thuringiensis (Bt) toxins and spinosyns, and plant-derived extracts like azadirachtin and pyrethrins are considered biologicals, they are still chemical molecules with many of the same hazards to human and environmental health as chemical pesticides (Dodia et al., 2010).

Biodiversity

Biodiversity enhances and maintains the supply of ecosystem activities and services, such as the generation of biomass, the cycling of nutrients, the support of soil carbon absorption, pollination, and the control of pests and diseases (van der Plas, 2019). Agricultural systems are vulnerable to diseases, pests, and environmental stressors like drought, and their biodiversity has been greatly reduced (Savary et al., 2019). In extensive farming, the use of artificial pesticides and fertilizers has detrimental effects on crop productivity as well as on the atmosphere. In a recent review, (de Vries, 2021) provided evidence, based on several field studies, of how nitrogen pollution from aerial deposition and agricultural runoff causes eutrophication and acidification in terrestrial ecosystems, which in turn causes species loss. These processes have cascading effects on the composition of communities across the food chain. Carvalho also described how pesticides may spread far from the locations where they are applied, building up in soils and food systems and having harmful impacts on species that are not intended targets, endangering ecosystems and public health (Carvalho, 2017). Disease risk is often correlated with increased biodiversity (Cappelli et al., 2022).

Agroecosystem services include many of the environmental benefits that biodiversity provides, such as pollination, preservation of nutrients, reducing weeds, and pathogen reduction, as they are crucial for the production of agricultural crops (Manning et al., 2019), (Duru et al., 2015). The goal of modern agriculture is to increase output in the near term. When fertilizers and insecticides are added to the farming systems of present crops, these crops yield well. In this case, additional species is probably only going to have a marginally positive impact on production (Manning et al., 2019). Diversification often has little effect on the primary crop's production (Tamburini et al., 2020). However, variety could also enhance other ecosystem services and possibly lessen the demand for fertilizer, irrigation, and pesticides (Manning et al., 2019). Crop diversity lowers disease levels, even when switching from single-species crops to dual planting (Letourneau et al., 2011). dditionally, the variation in trait expression is a powerful indicator of functional variety in agricultural ecosystems, which includes the suppression of weeds, retention of nitrogen (N), supply of inorganic N, enhancement of aboveground biomass, and occasionally yield (Finney & Kaye, 2017).

Although favorable links between biodiversity and ecosystem functioning may occur aboveground, there are also several mechanisms that can occur belowground. These include the processes related to resource division, breakdown, reduction of (underground) harmful microorganisms, and the choice of beneficial fungal and/or bacterial species (Thakur et al., 2021). Gaining a deeper comprehension of the mechanisms that propel these processes is essential for the advancement of environmentally friendly farming techniques (Mariotte et al., 2018).

Soil microorganisms that are beneficial may enhance the ability of plants to get nutrients, defend against threats, tolerate stress, collect nutrients in the community, and increase production (Finkel et al., 2017). Strategically using beneficial soil microorganisms in agricultural systems has the potential to decrease both ecological and economical expenses linked to the use of agrichemicals for the same purposes (Kleijn et al., 2019). Nevertheless, agricultural soils often have a limited number of microbial symbionts as a result of the detrimental effects of cultivation, pesticides, crop-switching trends (Bowles et al., 2017), and perhaps poor plant variety (McDaniel et al., 2014). Although it is well agreed upon that the variety of fungi that live under the ground may influence the nature and variety of plant communities, we have less knowledge of how a variety of plants affects the diversity of microorganisms in the soil (Philippot et al., 2013).

Relationships between BEFs are asymptotic. Therefore, communities with few species benefit most from the presence of new species (Cardinale et al., 2012), (Isbell et al., 2017). Hence, agricultural monocultures with tightly controlled plant diversity have a great deal of potential to enhance ecosystem functioning through diversification (Manning et al., 2019) across many temporal and geographical scales (Brooker et al., 2015). Here, we emphasize how plant diversity can support sustainable agriculture through both above- and below-ground processes. We do agree, though, that other management strategies—like conservation tillage, repurposing crop wastes, and integrated pest management—that have been the subject of more in-depth research will also be necessary to reap the benefits of variety (Tamburini et al., 2020).

Renewable Energy

It is projected that global energy consumption would rise by 50% by the year 2035 (Majed, 2022). The agriculture industry will be immediately impacted by this rise in energy demand because of the high energy required for different agricultural operations. This will also result in higher power costs. Food security will be in danger, especially in underdeveloped nations, by the rising cost of food production from agriculture due to the high input costs. This will also cause food prices to rise (Waseem et al., 2022). Implementing renewable energy sources in agricultural practices would enhance energy efficiency, availability of food, and preservation of the environment, aligning with the objectives of ecological agriculture. The use of energy in the globe is swiftly expanding, and that rise is matched by the widespread availability of fossil. While worldwide deposits of these hydrocarbons are fast depleting which is producing high energy prices owing to an unbalance in demand and supply (Majeed et al., 2023). Several uses of energy are achievable in agriculture (Schnepf, 2004). Direct energy refers to the energy used directly in a variety of agricultural processes, such as operating machinery and tools for various farm tasks, transportation vehicles, and equipment for climate control, such as dryers and coolers (Zhou et al., 2023). In contrast, the energy required to make herbicides, insecticides, and fertilizers for use in agriculture is referred to as indirect energy usage. For instance, between 1961 and 2008, the quantity of fertilizer needed in agriculture grew six times to fulfill the expanding worldwide need for food, even though the area utilized for cultivation remained relatively stable (Faostat, 2012). To create ammonia, about 94% of the energy used in agriculture is required (Mikkola & Ahokas, 2010). Also, the production of fertilizers for agriculture uses about 1.2% of all energy utilized worldwide (Majed, 2022)

Energy must be converted from one form to another for a task or process to be completed. There will inevitably be energy loss during this energy conversion process for several reasons. For instance, in order to operate an irrigation pump in agriculture, the chemical energy of fossil fuels must first be transformed into mechanical energy in order to drive the pump shaft. The water's potential energy is then obtained by transforming this mechanical energy into an upward force. The ratio of input to output energy is the measure of transformed energy efficiency. The fossil fuel that the pump uses in the aforementioned example is its input energy and the water that the pump discharges is its output energy. To reduce energy consumption and promote sustainability in energy management methods, efficient energy usage is essential (Majeed et al., 2023). The food and agriculture industries account for 30% of the world's energy use (Day, 2011). Thus, implementing energy-efficient farming practices is crucial to lessening the industry's excessive reliance on energy and lowering input costs, which will increase the sector's competitiveness in meeting the rising demand. Utilizing photovoltaic systems in residential buildings may help to promote sustainable agriculture by reducing energy shortages (P. Wang et al., 2022), (Huang et al., 2023). The agricultural industry has a wealth of these sources at its disposal. For instance, crops thrive in regions with year-round access to enough sunlight to sustain plant development. It means that solar panels can be utilized to easily capture sunshine energy, which can then be used to power a variety of agricultural equipment, such as irrigation water pumps.

Furthermore, owing to their flexibility and interoperability, electrochemical cells may assist in the effective and successful deployment of hydrogen energy in the agricultural industry (He et al., 2023) (Quan et al., 2023).

As an energy source that is renewable, wind energy can also be used by farmers to power their farms. In areas where wind energy is abundant, farmers can utilize wind turbines to generate electricity (Sun et al., 2023), (Chen et al., 2022). The electricity produced can power powerful machinery used in agriculture and in the processing of agricultural produce. Wind power plants in the United States are usually located in agricultural areas of the Midwest; because of their unique microclimate, wind turbines may affect crop growth (Munir et al., 2021), (Sutar & Butale, 2020).

Bioenergy is another important source of renewable energy and is widely available in agriculture (Saleem, 2022). According to research, bioenergy might provide 30–40% of the world's energy needs by 2050 (Errera et al., 2023). A large and affordable source of feedstock for bioenergy is the agricultural sector, which includes food crops, animal dung, and even urban waste. Nowadays, biofuels are ethanol based on sucrose or starch that is produced from biomass. High-octane ethanol can be directly used in internal combustion engines by mixing tiny amounts of it with gasoline. These engines can be used for a variety of farming-related duties, including machine operation, irrigation, and plowing (Majeed et al., 2023) .

The sun is the primary source of energy used by humans on Earth. "Solar" energy is defined as energy that is obtained directly from the sun. Alternative energy, solar power, ecological power, and environmentally friendly electricity are some names for renewable energy. A tiny amount of the sun's energy reaches Earth as radiation, even though the majority of it is captured by the surrounding stellar environment. In a single hour, solar radiation delivers more energy to the Earth's surface than all traditional sources of energy put together, including nuclear electricity, power from water, and petroleum-based products, can provide. About 4 million tons of solar fuel are converted into power every sec by the surface of the sun, in contrast. Compared to a nuclear reactor, which can produce 1000 megawatts of electrical power annually using 0.130 kg of nuclear fuel, this is significantly more (Majeed et al., 2023). The Earth's surface receives 1366 W of solar energy on average per square meter But this could change based on latitude (Herrería-Alonso et al., 2020).

One of the most established methods, solar irrigation, is used extensively to improve farming cycles and tolerance to changing rainfall patterns by increasing water access. Solar irrigation serves as a substitute for both present and future reliance on petroleum and coal as the irrigated area expands (Herrería-Alonso et al., 2020). Emissions are thereby decreased. Solar-powered pesticide sprayers are made for small-scale agricultural production to increase crop yields. These machines' compact overall design makes them easy to operate and transfer. They have PV panels and rechargeable batteries as well. In the food sector, baking is a very energy-intensive process that has grown increasingly difficult, particularly in poorer nations. Large amounts of thermal energy are utilized for heating on an industrial scale. Cooking is a significant procedure that uses a lot of energy, particularly in developing nations (Stoner et al., 2021). Compared to other culinary processes, baking requires a significantly higher quantity of energy. Fossil fuel consumption and the use of firewood contribute to environmental pollution and deforestation. To combat energy difficulties, it is therefore necessary to develop environmentally friendly technology for the food industry (Majeed et al., 2023).

Challenges in Sustainable Agriculture:

Adopting sustainable agricultural techniques has been demonstrated to increase crop yields and soil health in many situations; nevertheless, in order to fully realize the potential of these practices, several issues need to be resolved (Foley et al., 2011). A primary obstacle in sustainable agriculture is striking a balance between its various goals, which include increasing yield, protecting natural resources, and reducing its negative effects on the environment (Tsiafouli et al., 2015). It is imperative that trade-offs between these goals are recognized and resolved in order to successfully apply sustainable agriculture practices (Tittonell, 2014). The requirement for context-specific information and management techniques is another difficulty because the success of sustainable agriculture practices can vary based on several variables, including the specific kind of soil, climate, and local agronomic conditions (Giller et al., 2011). This emphasizes how crucial it is to fund extension programs and research in order to create and spread locally appropriate sustainable agriculture techniques (Garrity et al., 2010).

Furthermore, several obstacles, including a lack of information, insufficient access to resources, and unfavorable market and legislative conditions, may hinder the implementation of sustainable agriculture techniques (Knowler & Bradshaw, 2007). To build an environment that is conducive to the widespread adoption of sustainable agriculture techniques, a variety of stakeholders, including governments, researchers, farmers, and private sector players, must work together to overcome these obstacles (Pretty et al., 2006). Last but not least, new developments in biotechnology and digital agriculture present fresh chances to improve the effects of sustainable agricultural methods on crop yields and soil health (Rose et al., 2016). For example, advances in plant breeding may provide crop types that are more resilient to environmental hazards and resource-efficient, while remote sensing technologies may be employed to monitor indicators of soil health and have an impact on administration decisions (Iost Filho et al., 2020). Utilizing these technologies will be essential to sustainable agriculture's success in the future.

The advantages of organic amendments on many soil types, including clay (De Melo et al., 2019), loam (Dong et al., 2022), silty clay loam (D. Wang et al., 2022), and loamy sand (Li et al., 2021) have been demonstrated by several research. Diverse findings from recent studies have been drawn on the impacts of various organic additions on soil quality, providing insight into how these supplements affect different kinds of soil and when to apply them. A beneficial impact was seen in sandy and clay soils after 30 days of adding compost and vermicompost generated from organic waste and sewage sludge (Rivier et al., 2022). The research demonstrated how these additions, when applied quickly, may improve the condition of the soil. Conversely, after applying composted chicken manure at a rate of 9 t ha1 per year for 6 years (D. Wang et al., 2022) highlighted the considerable effects on silty clay loam soil. Farmyard manure (FYM) treatment has a short-term detrimental influence on soil composition and resilience against erosion, according to (Goldberg et al., 2020), in contrast to the beneficial impacts of other organic additions. In clay and sandy soils, this negative effect was shown just 21 days after application. These findings demonstrate the variety and temporal dependence of organic inputs' impacts on the condition of soil. The kind of soil and the timing of application determine how organic additions affect the quality of the soil. Although organic amendments typically raise the SOM content and encourage the production of aggregates, their effects may differ significantly based on the soil as well as how much time elapses. Studies conducted in the short term indicate that some additions, like FYM, may initially have negative impacts while others, like compost and vermicompost, have favorable effects. Extended application times may be necessary for notable enhancements in soil quality, according to research conducted over an extended period. For this reason, while using sustainable soil management techniques, it is crucial to take into account the kind of organic amendment and how long to apply it (Matisic et al., 2024).

Natural events and human activity on Earth produce temperature variations, which in turn start the concentration of greenhouse gases (Mentzafou et al., 2022). Ozone-depleting compounds, including methane, carbon dioxide (Rifai et al., 2023), and nitrous oxide, are caused by human activities to be released into the environment (Montzka et al., 2011). enhanced methane emissions from wetlands and nitrous oxide emissions from upland soils may be caused by higher levels of CO2 in the atmosphere (463–780 ppm), which would effectively offset the estimated 16.6% mitigation of climate change from an enhanced terrestrial carbon sink. These increased CO2 levels also affect the water content and microbial activity of the soil (Van Groenigen et al., 2011). Agriculture is the sector most vulnerable to climate change because of its vast scope and weather-related variability, which will have a major financial impact (Mendelsohn, 2009). Temperature and rainfall changes, among other climatic occurrences, have a significant influence on agricultural yield (Chiu et al., 2023). The crop type, location, and degree of parameter changes all affect the consequences of increasing temperatures, erratic precipitation, and CO2 fertilization. Although rising temperatures often result in yield reductions, these negative effects may be mitigated or neutralized by higher precipitation (Adams et al., 1998). Crop productivity in Iran is dependent on crop type, crop adaptation capacity, weather conditions, and the impact of CO_2, among other factors (Karimi et al., 2018). It is shown that a decrease in precipitation or an increase in temperature in Cameroon produces a sharp decline in producers' earnings. The lack of market demand for Cameroon's crop exports due to this issue and poor policymaking has resulted in unstable income levels in the nation (Molua, 2009). In addition, disorders and pest insects are prone to thrive in humid and warmer regions (Skendžić et al., 2021). Temperature, moisture, rainfall, and the speed of the wind all affect agricultural production; without any of all of these variables, there has been a chance that the costs of climate change have been overstated. Moreover, it was shown that China's yields of wheat, maize, and rice are expected to decrease by 18.26 ± 12.13, 45.10 ± 11.55, and 36.25 ± 10.75%, accordingly, until 2100 due to climate change (P. Zhang et al., 2017).

CONCLUSION

In conclusion, two significant objectives that can only be fulfilled through sustainable agriculture are reducing the degradation of the environment and providing the increasing demand for food on a global basis. By the adoption of cutting-edge technologies like precision farming and remote sensing, soil health management, and crop rotation, sustainable agriculture improves output while saving resources. Switching from traditional to ecological farming is essential for the environment's longevity, food safety, and economic security. Although the multiple benefits of implementing sustainable practices globally, there are still challenges to be addressed, including economic limitations, deficiencies of skills, and limited governmental support. States, educational institutions, growers, and business organizations have to work together to overcome these challenges and advocate the adoption of environmentally friendly farming methods. A considerable amount of study and investment for sustainable methods and technologies will be necessary for maximizing the farming industry to fulfill the demands of both the present and the future.

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