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Review Article

Modern Sociotechnical Practices for Sustainable Agriculture

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Abstract

Modern agricultural practices have significantly increased production through the use of chemical pesticides, inorganic fertilizers, and growth regulators. However, these methods have led to resource depletion, environmental degradation, and loss of crop diversity, highlighting their unsustainability. Sustainable agriculture emerged to address these issues, focusing on conserving natural resources and maintaining environmental quality.

Keywords: Modern Sociotechnical; Modern Agricultural; Chemical Fertilizers

Introduction

It's important to note that sustainable agriculture and organic agriculture are not the same. Sustainable agriculture allows limited use of chemical fertilizers and pesticides to avoid harmful effects on the soil and environment. In contrast, organic agriculture strictly avoids any chemical inputs. Both approaches aim to promote long-term agricultural viability, but they employ different methods to achieve this goal.

Necessary of sustainable agriculture

Sustainable agriculture is a broad term that encompasses various practices, including organic agriculture. It focuses on the successful management of agricultural resources to meet human needs while maintaining environmental quality and conserving natural resources. This balanced approach involves managing renewable resources such as soil, wildlife, forests, crops, fish, livestock, plant genetic resources, and ecosystems to prevent degradation, ensuring food security, livelihoods, and ecosystem services for current and future generations [1].

Sustainable agriculture promotes raising food that is healthy for consumers and animals, environmentally friendly, humane for workers, respectful of animals, fair for farmers, and supportive of rural communities. However, the term "sustainable agriculture" is often ambiguous and encompasses multiple approaches [2,3]. Different people and contexts interpret it differently, suggesting that instead of seeking a single, universal definition, we should adapt the concept of sustainable agriculture to fit specific contexts. This flexibility allows sustainable agriculture to be tailored to local needs and conditions, making it a versatile and practical approach to achieving long-term agricultural sustainability [4-7].

Sustainable agriculture systems are meticulously designed to leverage existing soil nutrient and water cycles, along with naturally occurring energy flows, for food production. These systems aim to produce nutritious food free from harmful substances that could impact human health. In practice, sustainable agriculture tends to minimize the use of chemical fertilizers, pesticides, growth regulators, and livestock feed additives. Instead, it relies on a combination of traditional and ecological methods to maintain soil fertility and productivity. These methods include

- **Crop Rotations:** Alternating different crops in the same field across seasons to improve soil health and reduce pest and disease cycles.
- **Crop Residues:** Using the remains of previous crops to enrich the soil with organic matter and nutrients.

- **Animal Manures:** Utilizing livestock manure to provide natural fertilizer, enhancing soil structure and nutrient content.
- **Legumes and Green Manures:** Growing legumes and other green manures that fix nitrogen in the soil, improving fertility and organic matter content.
- **Off-Farm Organic Wastes:** Incorporating compost and other organic wastes from external sources to add nutrients and organic matter to the soil.
- **Mechanical Cultivation:** Employing physical methods to control weeds and prepare the soil, reducing reliance on chemical inputs.
- **Mineral-Bearing Rocks:** Adding rock dust and minerals to replenish soil nutrients naturally.
- **Natural Biological and Cultural Controls:** Implementing biological controls, such as beneficial insects, and cultural practices, such as crop diversity and habitat management, to manage pests and diseases.

These practices collectively contribute to sustainable agriculture by enhancing soil health, reducing dependency on synthetic inputs, and promoting a balanced ecosystem that supports long-term agricultural productivity and environmental health.

These practices not only enhance soil health and biodiversity but also reduce dependency on synthetic inputs, fostering a more resilient and self-sustaining agricultural system. By integrating these methods, sustainable agriculture seeks to create a balanced ecosystem that supports long-term productivity and environmental health.

Between 1990 and 2015, the total forest area worldwide declined by three percent, decreasing from 4,128 million hectares to 3,999 million hectares. Agriculture has been identified as the most significant driver of this global deforestation [8]. A paper published by [9,10] indicates that between 1980 and 2000, over 55% of newly cultivated areas in tropical zones were developed at the expense of primary forests, with 28% of this expansion occurring at the cost of secondary forests. This extensive deforestation has been closely linked to biodiversity loss, with projections estimating that approximately 1 million species, including animals, plants, and insects, may face extinction in the coming decades to centuries.

Need of sustainable agriculture

Modern agricultural practices that rely heavily on chemical fertilizers and pesticides have led to numerous problems

- **Genetic Erosion:** The consistent use of a few high-yielding hybrid crop varieties has resulted in the depletion of traditional land varieties (desi varieties). These indigenous varieties are not only more nutritious but also possess valuable traits such as drought, disease, and pest resistance. The gradual loss of genetic diversity in both cultivated crops and their wild relatives, known as genetic erosion, is a significant concern. This diversity evolved over long periods and cannot be quickly replaced once lost.
- **Soil Erosion:** The overuse of inorganic fertilizers has degraded soil structure, making it more susceptible to erosion by water and wind. Fertilizers can destroy the soil's natural composition, leading to increased vulnerability to these erosive forces.
- **Soil Acidity:** Excessive use of nitrogenous fertilizers like urea has led to soil acidity. High nitrogen levels suppress beneficial biological activity, including mycorrhizae (symbiotic fungi that help plant roots absorb phosphorus), reduce nodulation in leguminous plants, give competitive advantages to weeds over crops, and increase pest incidence.
- **Water Management Issues:** Poor management of surface and groundwater resources has resulted in problems such as waterlogging, soil salinity, and alkalinity. Additionally, the excessive extraction of water for irrigation has caused a significant lowering of groundwater tables.
- **Deforestation:** Agricultural expansion has driven deforestation, contributing to global warming, the loss of biodiversity, drought, and the siltation of water reservoirs. This environmental degradation has far-reaching impacts on ecosystems and climate stability.

These challenges underscore the need for more sustainable agricultural practices that prioritize conservation of genetic diversity, maintenance of soil health, efficient water resource management, and forest preservation. Sustainable agriculture offers solutions to address these issues by promoting practices that support long-term agricultural productivity while minimizing environmental degradation.

Indeed, modern agricultural practices have contributed to ozone depletion and other environmental concerns:

- ****Ozone Depletion**:** Nitrous oxide (N2O) is a greenhouse gas produced by microbial activity on nitrogenous fertilizers. It is also a potent ozone-depleting substance. When released into the atmosphere, N2O can reach the stratosphere, where it reacts with ozone molecules, contributing to the thinning of the ozone layer. This thinning allows more harmful ultraviolet (UV) radiation from the sun to reach the Earth's surface, posing risks to human health and ecosystems.

- **Pesticide Resistance**: Excessive use of pesticides in modern agriculture has led to the development of pesticide-resistant pests. Over time, pests can evolve mechanisms to tolerate or resist the effects of pesticides, rendering them ineffective for pest control. This phenomenon results in a rise in pest populations and can lead to crop losses.
- **Environmental Pollution**: Pesticides used in agriculture can also contribute to environmental pollution. Runoff from fields can carry pesticides into nearby water bodies, contaminating aquatic ecosystems and harming aquatic life. Pesticides can also persist in the environment, accumulating in soil and water over time. Additionally, pesticide residues may enter the food chain, posing risks to human health through the consumption of contaminated food.

These environmental impacts highlight the need for sustainable agricultural practices that minimize the use of chemical inputs, promote integrated pest management strategies, and prioritize environmental protection. By adopting more sustainable approaches to agriculture, we can mitigate these negative effects and work towards a healthier and more resilient food system.

Management practices in sustainable agriculture

The management practices for sustainable agriculture virtually differ from those of modern agriculture. Generally, the management practices are adopted to achieve sustainable production with minimum or without using of chemical inputs with priority to farm-grown inputs without pollution and minimum damage to natural resource.

Conservation of crop diversity

The cultivation of high-yielding, fertilizer-responsive hybrid varieties over extensive areas has indeed led to the decline of traditional landraces (desi varieties). However, conserving these landraces is crucial not only for maintaining crop diversity but also for their potential future use in crop improvement programs. Desi varieties often possess valuable traits such as disease, pest, and drought resistance, as well as higher nutritive value, making them indispensable genetic resources.

Prioritizing the preservation and promotion of local or land varieties alongside hybrid varieties can help mitigate genetic erosion in agriculture. Genetic erosion refers to the loss of genetic diversity, including the loss of individual genes or entire species, which can undermine agricultural sustainability and resilience.

In addition to landraces, protecting the wild relatives of crops is essential for maintaining genetic diversity. These wild relatives often harbor valuable genes for resistance and adaptation. An exemplary case is Oryza nivara, a wild rice variety found in Central India. This wild rice species possesses a gene that confers resistance to grassy stunt disease in rice. Through plant breeding efforts at the International Rice Research Institute (IRRI) in the Philippines, this resistance gene was successfully incorporated into the world-famous International Rice 8 (IR8) variety of rice. This example underscores how genetic resources from wild relatives can be harnessed to enhance crop resilience and productivity. By prioritizing the conservation of landraces and wild relatives, and promoting the utilization of diverse genetic resources in crop improvement programs, agricultural sustainability can be enhanced. This approach not only safeguards against the risks of genetic erosion but also ensures a more resilient and productive agricultural system for the future.

Watershed management

Watershed is an area of land and water bounded by a drainage divide within which the surface runoff collects and flows out of the area through a single outlet into a river or other body of water. Watershed management is a holistic approach to bring about development of integrated farming systems on watershed basis. It aims at optimizing use of land, water, and vegetation in an area to mitigate drought, moderate floods, prevent soil erosion, improve water availability, and increase fuel, fodder and crop production on sustainable basis.Watershed management initiatives often include measures to protect and restore natural vegetation, such as reforestation, afforestation, and conservation of riparian buffers. Vegetation plays a critical role in watershed management, influencing water retention, soil stability, and biodiversity.

Efficient water management

Efficient water management is a central aspect of watershed management, involving strategies to conserve and manage water resources effectively. Key strategies include:

- **Rainwater Harvesting:** Capturing and storing rainwater for future use, this reduces dependency on traditional water sources and mitigates the effects of drought.
- **Construction of Check Dams and Ponds:** Building structures to slow down water flow, which helps in groundwater recharge, reduces soil erosion, and increases water availability during dry periods.
- **Soil and Water Conservation Measures:** Implementing practices such as contour plowing, terracing, and using cover crops to reduce runoff, prevent soil erosion, and enhance soil moisture retention.

By optimizing water use and reducing runoff, watershed management helps mitigate drought, moderate floods, and improve water availability for various uses, including irrigation, domestic, and industrial purposes. Sustainable land management practices are also integral to watershed management. These practices include

- **Agroforestry**: Integrating trees and shrubs into agricultural landscapes to improve biodiversity, enhance soil fertility, and provide additional sources of income.
- **Conservation Agriculture:** Employing minimal soil disturbance, maintaining soil cover, and practicing crop rotation to enhance land productivity while minimizing environmental degradation.

Together, these strategies support a holistic approach to managing water and land resources, promoting sustainable agriculture, and ensuring long-term environmental health and productivity.

Conservational tillage

Tillage practices in sustainable agriculture aim at reducing soil degradation and losses by erosion, with a focus on providing optimal conditions for beneficial soil organisms. These organisms enhance organic matter decomposition and nutrient cycling, which are crucial for soil health. Managing the top 8 cm of soil is vital because this layer hosts most of the biological activity, microorganisms, and organic matter. To achieve these goals, conservation tillage is adopted instead of conventional tillage.

Conservation tillage involves disturbing the soil to the minimum extent necessary and leaving crop residues on the soil surface. This approach includes

- **Minimum Tillage:** Tillage practices are reduced to the minimum extent necessary to ensure a good seed bed, rapid germination, and favorable growing conditions. This practice improves soil conditions due to the in situ decomposition of plant residues.
- **Zero Tillage:** An extreme form of minimum tillage where primary tillage (deep soil disturbance) is completely avoided. Secondary tillage (lighter operations) is confined to seed bed preparation in the row zone only. This results in soils that are homogenous in structure with more earthworms and increased organic matter content due to less mineralization. The presence of mulch reduces surface runoff.

Benefits of conservation tillage

- **Reduced Soil Loss:** Conservation tillage practices can reduce soil loss by up to 99% compared to conventional tillage. In most cases, they reduce soil loss by 50%.
- **Soil Structure and Organic Matter:** These practices maintain the organic matter content of the soil and prevent the removal of nutrients through rainwater. They also promote a homogeneous soil structure.
- **Microbial and Earthworm Populations:** Conservation tillage increases the populations of beneficial microorganisms and earthworms. These organisms play a critical role in nutrient cycling and soil aeration.
- **Enhanced Soil Moisture and Reduced Erosion:** The presence of crop residues on the soil surface reduces surface runoff and erosion while enhancing soil moisture retention.

By adopting conservation tillage practices, sustainable agriculture can effectively reduce soil degradation, enhance soil health, and improve overall agricultural productivity. These practices are essential for long-term environmental sustainability and agricultural resilience.

Nutrient management

The indiscriminate use of chemical fertilizers in modern agriculture to enhance crop yield has led to the degradation of land resources and stagnation in food grain production. Therefore, Integrated Nutrient Management (INM) is key to the success of sustainable agriculture. INM emphasizes the use of renewable sources of nutrients, which ameliorates soil health in the long run and ensures sustainability in agriculture.

Concept and Benefits

- **Diverse Nutrient Sources:** INM involves the application of all possible nutrient sources based on economic considerations. These sources include manures, green manures, compost, vermicompost, bio-fertilizers, and concentrated organic manures, supplemented with chemical fertilizers as needed to balance crop requirements [11], [12].
- **Long-term Soil Health:** Organic fertilizers have a slower action compared to chemical fertilizers but supply available nitrogen over a longer period. They protect the useful flora and fauna of the soil, improving yields and the quality of agricultural products. This practice increases soil fertility and maintains biological activity, ensuring the soil remains productive.

- **Sustainable Fertility Management:** INM allows for the safe disposal of crop residues and the production of high-quality compost, combining both organic and inorganic fertilizers to maintain soil fertility. It provides plants with the optimum level of nutrients required throughout their lifecycle, thereby sustaining yield [13] [14].

Implementation and impact

- **Balanced Application:** INM involves the careful application of chemical fertilizers alongside organic resources, maximizing their utilization efficiency. This balanced approach helps maintain agricultural productivity while protecting the environment for future generations [15].
- **Soil and Water Conservation:** By combining organic and inorganic fertilizer sources, INM enhances soil-water infiltration, reduces soil degradation, and promotes overall soil health, contributing to sustainable agricultural practices.
- **Food Security:** Achieving long-term food security necessitates balancing crop productivity with environmental sustainability. INM techniques help increase agricultural yield while minimizing environmental impacts, thus supporting future food supply needs.

Soil Fertility Management: Research has demonstrated that the application of soil fertility management technologies within INM increases agricultural yield by maximizing the efficiency of both fertilizers and organic resources.

Environmental Protection: Studies highlight that INM not only maximizes crop yield but also protects the environment by reducing chemical inputs and enhancing organic matter content.

By adopting INM, sustainable agriculture can effectively maintain soil health, enhance crop yields, and protect environmental resources, ensuring food security and sustainability for future generations [16-18].

Weed management

Techniques for controlling weeds include cultural, physical, biological, and chemical ones. Sustainable agriculture prioritizes biological, physical, and cultural processes. Hand weeding, tillage, and rotation are the usual methods used to control weeds. If the weed problem cannot be solved with the aforementioned techniques, chemical weedicides are also employed. Nonetheless, weeds are frequently accepted and even encouraged in sustainable agriculture since they serve important functions such as improving organic matter as green manure, controlling disease and pests, cycling nutrients, and conserving soil and moisture.

Pest management

Integrated Pest Management (IPM) is a sustainable approach to managing pests that combines various techniques to keep pest populations at manageable levels, minimizing economic damage and reducing environmental impact. This method addresses several issues caused by the overuse of chemical pesticides, including pesticide resistance, pest resurgence, and environmental pollution due to non-biodegradable substances.

IPM incorporates a range of strategies

- **Mechanical and Physical Methods:** These include manual techniques like hand-picking pests, using barriers to prevent pest entry, and employing traps to capture pests.
- **Cultural Methods:** These involve agricultural practices that reduce pest establishment, reproduction, and survival. Examples include crop rotation, intercropping, selecting pest-resistant crop varieties, and optimizing planting and harvesting times to avoid peak pest populations.
- **Biological Methods**: This strategy employs natural predators, parasites, and pathogens to control pest populations. Friendly insects and spiders, such as wolf spiders, sack spiders, diver spiders, orb spiders, and jumping spiders, are encouraged as they prey on pests, particularly in crops like rice.
- **Chemical Methods:** While chemicals are used in IPM, they are selected and applied in a manner that minimizes their impact on the environment, targeting specific pests and employing them as a last resort. The use of botanical pesticides, which are derived from plants, is also a part of this strategy.
- **Botanical Pesticides:** These are natural pesticides derived from plants that are less harmful to the environment compared to synthetic chemicals. They help control pests while being biodegradable and often less toxic to non-target organisms.

An essential component of IPM is the use of an action threshold. This threshold is the point at which pest populations or environmental conditions indicate that pest control action must be taken to prevent unacceptable economic harm. It emphasizes that not all pests require intervention, only when they pose a significant risk [19,20].

IPM relies on comprehensive, up-to-date information about pest life cycles and their interactions with the environment. By integrating multiple control strategies and closely monitoring pest populations, IPM ensures that pest management is both cost-effective and environmentally sound. This holistic approach helps maintain a balance in the ecosystem, reducing reliance on chemical interventions and promoting sustainable agriculture [21,22].

Crop diversification

Crop diversification plays a crucial role in enhancing crop production and ensuring agricultural sustainability. Methods such as crop rotation, mixed cropping, and intensive cropping are employed to achieve these goals while also mitigating soil erosion and improving soil fertility.

- **Crop Rotation:** This practice involves alternating the cultivation of different crops on the same piece of land over time. It helps manage soil fertility by preventing nutrient depletion and reduces the build-up of pests, diseases, and weeds associated with monoculture. Including leguminous crops in rotation adds nitrogen to the soil, further enhancing its fertility.
- **Mixed Cropping:** In mixed cropping, two or more crops are grown together in the same field. This approach provides several benefits, including risk mitigation against adverse weather conditions or pest outbreaks. Leguminous crops are often included in mixed cropping systems to improve soil nitrogen levels and increase the yield of non-leguminous crops.
- **Intensive Cropping:** Intensive cropping involves growing multiple crops simultaneously within a single agricultural year on the same plot of land. This method aims to maximize production per unit of land and time. Examples include multiple cropping, where three or four crops are cultivated successively within a year, and relay cropping, where one crop is sown or harvested while another is growing.

These practices contribute to sustainable agriculture by optimizing land use, reducing soil degradation, enhancing biodiversity, and improving resilience to environmental challenges. By diversifying crop systems, farmers can achieve higher yields, better manage pests and diseases, and maintain the long-term productivity of their farmland. Overall, crop diversification strategies are essential for sustainable food production and ensuring food security in the face of changing climate conditions and increasing pressure on natural resources.

Organic farming

Organic farming represents a holistic approach to agriculture that prioritizes environmental protection, animal welfare, food quality and safety, resource sustainability, and social justice. This method emphasizes the use of natural and renewable resources, the management of ecological processes, and the promotion of biodiversity [23]. Organic farming aims to create integrated, humane, and economically sustainable production systems that provide acceptable levels of nutrition while minimizing the negative impacts on the environment and society.

A modern definition of organic farming, as provided by authoritative sources, underscores the importance of maximizing reliance on farm-derived renewable resources and managing ecological and biological processes and interactions [24]. This approach aims to ensure crop, livestock, and human nutrition, protection from pests and diseases, and an appropriate return to human and other resources [25]. Despite its significant benefits and increasing global attention, organic agriculture still represents a small fraction of total agricultural land, accounting for only 1.5 percent as of 2018. However, there has been a growing trend towards organic farming, with over 186 countries actively implementing organic practices. This trend is evidenced by the increasing number of farmers engaging in organic farming, reaching 2.8 million in 2018 [26]. As the demand for organic products continues to rise and consumers become more aware of the environmental and health benefits of organic farming, there is potential for further expansion of organic agriculture worldwide. By promoting sustainable farming practices and supporting organic producers, societies can move towards more environmentally friendly and socially responsible food systems.

Integrated farming

The concept of Integrated Farming Systems (IFS) represents a departure from traditional monoculture farming towards a more holistic and interconnected approach to agriculture. Integrated farming systems involve the combination of different agricultural activities, such as livestock and crop production, or fish and livestock production, within a single farming operation [27,28]. In an Integrated Farming System, various components are interconnected in a way that waste or by-products from one component serve as inputs for another, creating a synergistic relationship among different elements of the farm [29]. For example, livestock waste can be utilized as fertilizer for crop production, while crop residues can be used as feed for livestock. Similarly, fish farming waste can be recycled to fertilize crops or feed other livestock.

This approach helps to optimize resource utilization, reduce waste, and improve overall productivity and revenue for the farming system. By integrating different components, farmers can achieve greater efficiency in resource management and enhance the sustainability of their operations. Additionally, integrated farming systems often result in diversified income streams for farmers, reducing their dependency on a single crop or livestock product [30-32].

Overall, Integrated Farming Systems represent a more sustainable and resilient approach to agriculture, which not only reduces environmental impact but also enhances economic viability for farmers. By embracing the principles of integration and resource efficiency, farmers can create more resilient and productive farming systems for the future.

Conclusion

Comparing sustainable agriculture to modern agriculture reveals several advantages: it is less expensive, preserves soil, water, and air, maintains crop diversity, and yields nutrient-dense, pesticide-free food grains. With consideration for both socioeconomic and environmental concerns, sustainability is the goal of all the approaches. The application of innovative farming techniques in harmony has shown them to be beneficial in attaining sustainability. Agroforestry, precision farming, integrated nutrient management, integrating livestock and crops, planting cover crops and perennials, decreasing or eliminating tillage, rotating crops, embracing diversity, applying integrated nutrient management, and applying integrated pest management (IPM) are a few of the sustainable agricultural practices. In order to ensure ecological sustainability and food security for the world's rapidly growing population, innovative agricultural techniques and ideas must be put into reality. The preservation of nature and its advantages for humankind can only be guaranteed by drastic transformation towards a sustainable global economy. It has been demonstrated that these methods and approaches are environmentally beneficial. For the purpose of protecting the environment, natural resources, crop diversity, and the production of wholesome food grains, a transition from modern to sustainable agriculture is thus urgently needed.

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