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Sustainable agricultural practices: Addressing climate change and food security challenges

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Abstract
Climate change and environmental degradation pose significant threats to global agriculture and food security. Herbal traditional farming techniques lead to deteriorating soils as well as diminishing biodiversity together with decreasing water resources. An assessment of sustainable agricultural practices comprises agroecology alongside organic farming and regenerative agriculture, conservation agriculture and precision farming. These methods improve soil health through optimized resource usage which generates economic value and maintains social responsibility as they decrease environmental damage. The long-term preservation of food security requires sustainable agriculture although it faces hurdles such as initial capital expense and policy barriers and information deficits. The transition to resilient sustainable agricultural practices needs integrated scientific advances from experts while providing farmers educational support by authorities in order to boost the pace of change.

Keywords: Sustainable agriculture, climate change, food security, precision farming and agroecology

Introduction
Climate change has emerged as a critical concern over the past several decades and its impacts are becoming more apparent with each passing year. The planet's climate is undergoing significant transformations, characterized by long-term shifts in temperature and weather patterns. These changes are primarily propelled by human activities, particularly the combustion of fossil fuels, widespread deforestation and alterations in land use (Wuebbles and Jain, 2001) [47]. The implications of climate change for agriculture are profound and multifaceted. Farmers are witnessing alterations in growing seasons, with some areas experiencing shorter periods suitable for cultivation while others may see extended growing windows. Additionally, changing precipitation patterns are leading to unpredictable rainfall, which can result in either drought conditions in some regions or excessive flooding in others (Trenberth, 2005) [46]. Moreover, the increasing frequency and intensity of extreme weather events, such as hurricanes, heat waves and severe storms, pose additional risks to crop yields and livestock health. The shifts in climate are also driving the geographical redistribution of agricultural zones, forcing farmers to adapt to new regions where traditional crops may no longer thrive. These interconnected challenges underscore the urgent need for sustainable practices and innovative solutions within the agricultural sector to mitigate the adverse effects of climate change (Giller *et al*, 2021) [16].

Intensive farming practices such as monoculture and tillage, excessive use of chemical fertilizers and pesticides, conversion of forest to cropping lands have severely impacted the environment. These practices result in soil degradation, water pollution, loss of biodiversity and contribute to climate change (Belete and Yadete, 2023) [3].

Global food security is a complex and multifaceted issue that impacts millions of people around the world. It is defined by the availability, access, utilization and stability of food supplies needed to meet everyone's dietary requirements. While significant progress has been made in reducing hunger and improving food security in recent decades, approximately 820 million people still suffer from hunger and around 1.3 billion people face moderate to severe food insecurity (Mohajan, 2022) [27]. In stark contrast, about one-third of all food produced globally is lost or wasted, which amounts to roughly 1.3 billion tonnes of food annually. Challenges such as population growth, urbanization, environmental degradation and economic inequality continue to threaten global food security.

Considering the on-going challenges in agriculture, adopting sustainable practices is essential for addressing these issues. Sustainable agriculture takes a comprehensive approach that tackles the environmental, social and economic challenges faced by the sector today.

Sustainable agriculture is a system of farming practices that are environmentally sound, economically viable and socially responsible (Allen, 1991) [1]. It aims to meet the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable agriculture mainly concentrating on the practices which focuses on environmental sustainability, economic viability and social responsibility (Pretty, 2008) [35]. Environmental sustainability is attained by adopting practices that conserve natural resources such as soil, water and biodiversity (Jhariya *et al*, 2021) [21]. It also involves minimizing pollution from pesticides, fertilizers, and other agricultural inputs, promoting healthy ecosystems, and reducing greenhouse gas emissions (Rehman, 2022) [37]. Key practices that support environmental sustainability include crop rotation, cover cropping, integrated pest management, and conservation tillage.

Economic viability in farming ensures that operations are profitable, enabling farmers and their families to thrive. It promotes fair market access and equitable distribution of resources, encouraging diversification of crops and livestock to reduce risk. The goal is to produce food in a manner that enables farms to remain sustainable in the long term. Social responsibility focuses on the well-being of farmers, farm workers and rural communities. It promotes food security and ensures access to healthy food for everyone while respecting cultural traditions and agricultural knowledge. Additionally, it advocates for safe working conditions and fair wages (Bowman and Zilberman, 2013) [6]. This article aims to discuss the current state of sustainable practices and their potential to ensure a food-secure future.

Current state of agriculture

India has made significant progress in food security and has become one of the world's largest suppliers of rice, wheat, sugar, and cotton (Dev and Sharma, 2010) [12]. The agriculture sector occupies nearly 47% of the country's geographical area and provides employment for over 50% of the population (Blyn, 2016) [4]. However, Indian agriculture faces several challenges. One major issue is soil degradation, which affects 173.65 million hectares of land out of a total geographical area of 328.9 million hectares. This degradation is primarily caused by deforestation, improper drainage, overgrazing, and the excessive use of agrochemicals (Sharma *et al*, 2018) [41]. Addressing these challenges is crucial for sustaining agricultural productivity and ensuring long-term food security in India.

Water scarcity has emerged as a pressing issue, demanding our immediate attention. Since the mid-20th century, specifically after 1950-51, the reliance on groundwater has escalated dramatically, highlighting our increasing struggle to secure sustainable water sources. Currently, we tap into 50% of our available groundwater reserves, with a staggering annual consumption rate of 245 billion cubic meters (Panjabi, 2013) [32]. This immense volume equates to billions of litres being drawn from our aquifers each year, raising concerns about the long-term viability of this precious resource. As we face the consequences of unsustainable usage, it becomes crucial to adopt measures that not only preserve our groundwater but also promote the responsible management of our overall water supply for the well-being of future generations.

Conventional agricultural practices are widely used around the world, but they have significant environmental impacts (Srednicka-Tober *et al*, 2016) [44]. Intensive tillage and the monoculture of crops over large areas can lead to soil erosion, nutrient depletion and reduced soil fertility (Belete and Yadete, 2023) [3]. The excessive use of fertilizers and pesticides can result in biodiversity loss and eutrophication and these chemicals can contaminate groundwater and surface water through leaching (Khan *et al*, 2018) [24]. Additionally, monoculture and intensive farming practices contribute to the loss of crop diversity, soil biota and beneficial insects. Conventional agriculture also plays a role in climate change by releasing greenhouse gases such as nitrous oxide and methane (Xing and Wang, 2024) [48]. Furthermore, the overuse of pesticides can lead to the development of pesticide-resistant pests, diminishing their effectiveness (Zhou *et al*, 2024) [50]. Addressing the challenges facing Indian agriculture requires a multi-faceted approach that incorporates sustainable agricultural practices in India.

Sustainable agricultural practices

a) Agro ecology

Agro ecology is an approach to agriculture that focuses on the health of the entire ecosystem, which includes soil, water, air, plants, animals and humans. It involves creating and managing agricultural systems that are diverse, resilient and adaptable. These systems promote ecological balance and biodiversity (Yadav *et al*, 2021) [49]. The application of scientific principles in agriculture leads to the development of diverse agro ecosystems that enhance environmental sustainability. This approach emphasizes the importance of various ecosystem services, such as maintaining soil fertility, facilitating biogeochemical cycling and ensuring effective nutrient exchange between crops and the soil. An integrated approach that combines diversified crop cultivation with animal husbandry practices can effectively tackle food security challenges and contribute to the creation of climate-resilient agro ecosystems. Furthermore, these agro ecosystems play a crucial role in supporting daily livelihoods, as they provide essential resources like fuel, fodder and food for rural communities, thereby promoting the socioeconomic well-being of populations worldwide.

Agro ecology promotes the cultivation of a diverse range of crops and supports ecosystems that are beneficial for insects, pollinators, and organic pest management. By emphasizing organic matter and natural fertilizers, it enhances long-term productivity by improving soil fertility and structure, while also reducing erosion. Agro ecological practices, such as agroforestry and crop diversification, increase resilience to extreme weather events, aiding in climate change adaptation.

Moreover, water resources can be conserved through methods like contour farming, rainwater collection and efficient irrigation systems. Agro ecology also minimizes threats to the health of consumers and farmers, as well as to the environment, by reducing the use of synthetic inputs like fertilizers and pesticides. Diverse farming systems contribute to a wider range of nutrients in diets, which improves overall nutrition and health outcomes.

In addition, agro ecology empowers communities socially and economically by promoting farmer autonomy, facilitating knowledge exchange and encouraging local decision-making. It advocates for land-use practices that protect biodiversity and natural habitats by restoring and maintaining ecosystems (Gliessman *et al*, 1998; Franzluebbers *et al*, 2020 Yadav *et al*, 2021; Munira and Deepika, 2024) [18, 13, 49, 28].

b) Organic farming

Organic farming is a sustainable approach to agriculture that prioritizes the use of natural and locally available materials to promote soil health, biodiversity, and ecosystem services. Organic farming promotes the use of natural and locally available materials, such as compost, manure and green manure, to maintain soil fertility and promote plant growth. Organic farming avoids the use of synthetic fertilizers, pesticides and genetically modified organisms (GMOs) to promote ecosystem health and biodiversity (Ceccarelli, 2014) [8].

Organic farming promotes soil health through the use of natural amendments, conservation tillage, and cover crops, reducing soil erosion and degradation (Crystal-Ornelas *et al*., 2021) [10]. Organic farming maintains ecological balance by promoting biodiversity, using crop rotation, and preserving natural habitats (Gamage *et al*, 2023) [14]. Organic farming encourages efficient water use through drip irrigation, mulching and conservation tillage (Tiwari *et al*, 2023) [45]. Organic farming reduces greenhouse gas emissions by promoting soil carbon sequestration, reducing synthetic fertilizer use and enhancing ecosystem resilience (Scialabba and Müller-Lindenlauf, 2010) [39]. Organic farming promotes fair labour practices, ensuring safe working conditions, fair wages and social protection for farmers and farmworkers (Shreck *et al*, 2006) [43]. Organic farming contributes to community development by promoting local food systems, supporting small-scale farmers, and enhancing rural livelihoods (Jouzi *et al*, 2017) [22]. Organic farming enhances food security and sovereignty by promoting local food production, improving access to nutritious food, and supporting community-led agricultural initiatives (Burdock and Ampt, 2017) [7].

Organic farming promotes soil health, biodiversity and ecosystem services, leading to improved crop yields and quality. Organic farming can increase farmer incomes through premium prices for organic products, reduced input costs and improved market access. Organic farming reduces environmental costs by minimizing the use of external inputs, conserving natural resources and promoting ecosystem services (Panwar *et al*, 2022) [33].

c) Regenerative agriculture

Regenerative agriculture is a holistic approach to farming and land management that goes beyond sustainability to restore and enhance the health of ecosystems, soil and communities (Babaniyi *et al*, 2024) [2]. It focuses on practices that help rebuild soil fertility, increase biodiversity, improve water retention and sequester carbon. This approach aims to regenerate the land rather than merely maintain its current state, addressing long-term environmental and social challenges. By using practices like no-till farming, crop rotation and the use of cover crops, regenerative agriculture prioritizes soil health. Healthy soil is rich in organic matter, supports diverse microbial life, and is more resilient to drought, erosion and disease. Diverse ecosystems are encouraged on farms, including a variety of plants, animals, and beneficial insects. This helps in pest control, pollination, and overall ecosystem stability. Instead of synthetic fertilizers and pesticides, regenerative agriculture focuses on natural fertilizers such as compost, manure and bio fertilizers. These improve soil structure, increase microbial diversity and reduce dependency on external inputs (Sherwood and Uphoff, 2003; Giller *et al*, 2021; Khangura *et al*, 2023) [42, 17, 25].

When livestock is part of the farm, regenerative practices use rotational grazing systems to avoid overgrazing, promoting healthy pastures, and restoring degraded land. Integrating trees into agricultural landscapes enhances biodiversity, improves soil health, and can help sequester carbon (Pandao *et al*, 2023) [31]. Techniques like contour farming, rainwater harvesting and key line design help manage water efficiently, reducing runoff and improving water retention in the soil (Madhu, 2022) [26]. Through improved soil and plant management, regenerative agriculture increases the ability of the land to capture and store carbon, mitigating climate change (Ghosh *et al*, 2024) [15].

d) Conservation agriculture

Conservation Agriculture (CA) is a farming approach that promotes sustainability by minimizing soil disturbance, maintaining soil cover, and promoting crop rotations. Conservation agriculture emphasizes practices like minimal soil disturbance (no-till or reduced tillage), crop rotation and cover cropping. These techniques maintain or even increase soil organic matter, which improves soil structure, fertility, and water-holding capacity. By improving soil structure and increasing organic matter, conservation agriculture helps soils retain moisture, reducing the need for irrigation (Hobbs *et al*, 2008) [20]. This is especially important in drought-prone areas, making water use more efficient and sustainable. Crop rotation and the inclusion of cover crops provide diverse habitats for beneficial organisms like earthworms, insects and microbes. This boosts biodiversity in farming ecosystems, which supports pest control, pollination, and nutrient cycling. Minimal tillage and ground cover protect the soil from wind and water erosion. This is important for maintaining fertile topsoil, which is essential for future food production and preventing land degradation. By increasing soil organic matter, conservation agriculture helps sequester carbon from the atmosphere, reducing greenhouse gas emissions. This contributes to climate change mitigation efforts (Hobbs, 2007). [19]

Crop rotation and diversification promote natural pest control mechanisms, which reduce the need for chemical pesticides. This also protects local ecosystems and human health. With reduced need for fertilizers, pesticides and irrigation, farmers can lower their operating costs. Over time, the soil health improvements can lead to higher yields with less input. Over time, CA systems maintain or even increase productivity by improving soil health, reducing pest pressures and making farming systems more resilient. This supports long-term food security (Pretty *et al*, 2006; Kassam *et al*, 2009; Palm *et al*, 2014) [36, 23, 30].

e) Precision agriculture

Precision farming (also known as precision agriculture) plays a significant role in enhancing sustainability by using advanced technologies to manage crops and resources more efficiently. This approach helps optimize input use, reduce waste and increase productivity while minimizing environmental impact (Pierce and Nowak, 1999; Shafi *et al*, 2019) [34, 40]. Precision farming utilizes data from GPS, sensors, drones and satellite imagery to precisely apply water, fertilizers, pesticides, and herbicides where they are needed, reducing waste and overuse. This leads to lower input costs, less pollution, and improved environmental health. Precision irrigation systems monitor soil moisture levels and weather forecasts to deliver the right amount of water only when necessary. This reduces water consumption, minimizes runoff, and helps conserve this critical resource. By using sensors and mapping technologies, precision farming can apply different amounts of inputs based on soil health and nutrient requirements in specific areas of the field. This prevents over-fertilizing and under-fertilizing, which can both degrade soil health in different ways (Bongiovanni and Lowenberg-DeBoer, 2006) [5].

Precision farming tools can continuously monitor soil conditions, such as pH, texture, moisture and organic matter. By regularly checking soil health, farmers can adjust their practices to prevent soil degradation and erosion, ensuring long-term soil fertility. Precision farming uses technology like drones and sensors to detect pests or diseases early, allowing farmers to apply pesticides only when necessary and in precise amounts. This minimizes the need for broad-spectrum pesticide applications, protecting pollinators, beneficial insects and surrounding ecosystems. Through advanced monitoring tools, precision farming can also help farmers identify pest infestations before they spread, leading to more targeted and efficient pest management (Oliver *et al*, 2013) [29].

With data from precision tools, farmers can optimize planting density and placement, ensuring that crops grow in their ideal conditions. This maximizes yields while minimizing wasted space or underutilized areas. By using precise data to adjust practices such as planting, irrigation and fertilization, farmers can significantly increase crop productivity, reducing the need for additional land or resources and ensuring food security. Precision farming enables farmers to collect real-time data on crop performance, weather patterns, soil conditions and more. This allows for informed decision-making, leading to more sustainable farming practices by adjusting to changing conditions. Using historical and real-time data, farmers can predict crop outcomes, optimize planting schedules, and forecast potential risks (like pest outbreaks or extreme weather). This enables proactive rather than reactive approaches, further improving sustainability (Cox, 2002) [9].

Challenges and limitations

Sustainable agriculture aims to balance environmental health, economic profitability, and social equity. However, several challenges and limitations hinder its widespread implementation. Sustainable agricultural practices, may require higher upfront costs for inputs, equipment, and training. Also, these practices result in lower yields, at least in the short term, which can affect farmers income. The resultant products require access to specialized markets and premium prices, which can be challenging for small- scale farmers.

Farmers may require new knowledge and skills to adopt sustainable agricultural practices, such as integrated pest management, conservation agriculture and precision farming. Small scale farmers have limited access to technology, which will create problems in adopting precision agriculture tools or advanced irrigation system management. Sustainable agricultural practices may require specific soil and water conditions, which can be challenging in areas with poor soil health or limited water resources.

In addition to that, sustainable agricultural practices may conflict with traditional farming practices and cultural values, which can make adoption challenging. These practices may require changes in social norms and behaviours, which can be challenging for farmers and rural communities. Moreover, sustainable agricultural practices require policy support, subsidies and tax incentives. Despite these challenges, sustainable agricultural practices remain essential for ensuring long-term food security and environmental protection. Addressing these limitations requires a multidisciplinary approach involving scientific research, policy reforms, financial support and farmer education.

Conclusion

Sustainable agriculture is vital for mitigating climate change, preserving natural resources, and ensuring food security. Agroecology, organic farming, regenerative agriculture, conservation agriculture and precision farming offer viable solutions to current agricultural challenges. While barriers such as cost, knowledge gaps and policy limitations hinder widespread adoption, targeted efforts in research, education and government support can drive progress. Sustainable practices not only enhance environmental health but also promote economic stability and social well-being. A holistic approach that integrates technology, traditional knowledge and policy reforms will be essential for transitioning towards a more resilient and food-secure future, benefiting both present and future generations.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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Competing Interests

Authors have declared that no competing interests exist.

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