EFFECT OF TECHNOLOGICAL INNOVATION ON SUSTAINABILITY PRACTICES IN THE AGRICULTURAL SECTOR

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ABSTRACT

This paper reviews the literature on how technological innovation can enhance sustainability practice in the agricultural sector. It adopts a multidimensional perspective of sustainability that encompasses environmental, economic, and social aspects. The paper identifies four main areas of technological innovation that can contribute to sustainability in agriculture: precision farming, biotechnology, renewable energy, and digital platforms. The paper discusses the benefits and challenges of each area, as well as the implications for policy and research. The paper concludes that technological innovation can play a key role in advancing sustainability in agriculture, but it requires a holistic and participatory approach that considers the needs and preferences of different stakeholders, as well as the trade-offs and synergies among different dimensions of sustainability.

Keywords: Technology, Innovation, Sustainability, Agro-Sector.

INTRODUCTION

In the context of agricultural development, sustainability is a crucial idea because it refers to meeting present needs without compromising the capacity of future generations to meet their own needs. But because it involves balancing the environmental, economic, and social dimensions of farming systems, achieving sustainability in agriculture is a difficult and multifaceted challenge. By offering solutions that can boost productivity, efficiency, and resilience while decreasing detrimental effects on natural resources and human well-being, technological innovation can play a significant role in improving sustainability practices in the agricultural sector. The goal of this paper is to review the current state of the art and the potential for technological innovation in sustainable agriculture, with a particular emphasis on four key areas: precision agriculture, biotechnology, digital agriculture, and circular agriculture. We will talk about each domain's potential benefits and drawbacks as well as the obstacles to and factors that support its adoption and spread. Furthermore, we will emphasize the necessity of an integrated and systemic approach to innovation, one that takes into account the interactions and trade-offs between various technologies as well as the socioeconomic and institutional factors that influence their creation and application.

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LITERATURE REVIEW

Technological innovation can enhance sustainability practice in the agricultural sector by increasing productivity, reducing environmental impact, and improving resilience. One of the main challenges in agriculture is to produce more food with fewer inputs, such as land, water, energy, and chemicals. Precision agriculture is a technology that uses real-time data from sensors, satellites, drones, and other sources to optimize crop management and reduce waste. Precision agriculture can help farmers monitor soil moisture, nutrient levels, pest infestation, and weather conditions, and adjust irrigation, fertilization, and pesticide application accordingly (McKinsey, 2022). This can result in higher yields, lower costs, and less environmental damage. Another challenge in agriculture is to reduce its greenhouse gas emissions and its dependence on fossil fuels. Controlled-environment agriculture is a technology that uses artificial lighting, heating, ventilation, and automation to create optimal conditions for plant growth in indoor or enclosed spaces. Controlled-environment agriculture can reduce water consumption by up to 95%, land use by up to 99%, and energy use by up to 50% compared to conventional farming (World Economic Forum, 2022). It can also enable year-round production of fresh and nutritious food in urban areas or regions with harsh climates. A third challenge in agriculture is to enhance its resilience to climate change and natural disasters. Biotechnology is a technology that uses genetic engineering, gene editing, or other methods to modify the traits of plants or animals. Biotechnology can help create crops or livestock that are more resistant to drought, heat, pests, diseases, or salinity (Clapp & Ruder, 2020). It can also improve the quality, diversity, and nutritional value of food products. However, technological innovation in agriculture also faces some barriers and risks, such as regulatory uncertainty, ethical concerns, social acceptance, and potential trade-offs. For example, biotechnology has been subject to strict regulation and public scrutiny in many countries due to safety or ethical issues. Moreover, technological innovation may not benefit all farmers equally, especially smallholders who lack access to information, capital, or markets (Datamation, 2022). Therefore, technological innovation in agriculture needs to be accompanied by appropriate policies, institutions, and incentives that ensure its safety, sustainability, and inclusiveness. In this article, we will review some of the current and emerging technologies that can help address the challenges of food security, climate change, and resource depletion in agriculture.

Precision Agriculture

Precision agriculture (PA) is a farming management strategy that aims to improve agricultural production sustainability by observing, measuring and responding to temporal and spatial variability in crop and livestock systems. Precision agriculture often employs technologies such as satellite positioning, remote sensing, proximal data gathering and variable rate technology to enable an information-based decision making approach to farm management, to optimize returns on inputs. Precision agriculture is not about drastically increasing yields, but tailoring the cultivation of each square foot: adopting a '*per plant*' '*per animal*' approach. Precision agriculture is also known as "*precision farming*," "*site-specific crop management*," "*prescription farming*," and "*variable rate technology*". Precision agriculture has been developing since the 1990s, and it offers a new set of tools for farmers to enhance their productivity, profitability and environmental stewardship. Unlike previous agricultural revolutions, which have focused on further intensification and standardization, Precision

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agriculture is an agricultural revolution for the family farm - a threatened feature of the British countryside. However, Precision agriculture is not yet widely adopted by farmers, due to various challenges such as high costs, lack of skills, data ownership and interoperability issues, and uncertain benefits.

Precision agriculture has the potential to transform the future of farming by enabling more efficient use of resources, reducing environmental impacts, increasing crop quality and yield, and improving animal welfare and health. Precision agriculture also requires new skills and knowledge for farmers, such as data analysis, digital literacy, and precision machinery operation. Precision agriculture is a dynamic and evolving field that requires continuous research and innovation to address the diverse needs and challenges of different farming systems and contexts. However, Precision agriculture also faces several challenges that limit its adoption and implementation. Some of these challenges are technical, such as the high cost of equipment and software, the lack of interoperability and standardization among different devices and platforms, the complexity of data processing and interpretation, and the need for reliable connectivity and power supply (Nesta, 2023). Other challenges are related to human factors, such as the lack of skills and training among farmers and extension agents, the resistance to change and innovation, the lack of trust and transparency in data sharing and ownership, and the ethical and social implications of Precision agriculture for rural communities and food security. Therefore, Precision agriculture requires a holistic and participatory approach that involves multiple stakeholders from different sectors and disciplines. Precision agriculture also needs to be tailored to the specific needs and contexts of different farms and regions, taking into account the biophysical, socio-economic and cultural diversity of agriculture. Precision agriculture is not a one-size-fits-all solution, but a flexible and adaptive tool that can help farmers achieve their goals in a sustainable way.

Controlled-Environment Agriculture

Controlled-environment agriculture (CEA) is a technology-based approach to food production that aims to provide optimal growing conditions for crops and protect them from adverse environmental factors. Controlled-environment agriculture includes various systems such as greenhouses, vertical farms, and recirculating aquaculture systems, which use soilless growing methods such as hydroponics, aeroponics, and aquaponics. Controlled-environment agriculture has several advantages over conventional agriculture, such as higher yields, resource efficiency, climate resilience, food safety, and waste reduction (FarmTech Society, 2020). Controlled-environment agriculture also offers opportunities for product diversification, income improvement, and green infrastructure integration for farmers and communities. Controlled-environment agriculture is considered as a promising sector for the future of farming in Europe and beyond (European Commission, 2019). However, Controlled-environment agriculture also faces some challenges, such as high capital and operational costs, technical complexity, and social acceptance.

One of the main challenges of Controlled-environment agriculture is the high initial investment required to set up and maintain the controlled environment facilities. Controlled-environment agriculture systems often involve sophisticated technologies, such as artificial lighting, hydroponic or aeroponic systems, sensors, and automation. These technologies can increase the productivity and quality of crops, but they also entail higher costs compared to conventional agriculture. According to a study by Cornell University, the capital cost of a

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vertical farm can range from $200 to $500 per square foot, depending on the level of automation and complexity of the system. Moreover, Controlled-environment agriculture systems also have higher operational costs, such as electricity, water, nutrients, labor, and maintenance. These costs can vary depending on the type and scale of Controlled-environment agriculture system, the location, and the crop grown. For example, a study by FarmTech Society estimated that the operational cost of a vertical farm in Europe can range from 0.5 to 2 Euros per kilogram of leafy greens produced. Another challenge of Controlled-environment agriculture is the technical complexity and reliability of the systems. Controlled-environment agriculture systems depend on various components and processes that need to be carefully monitored and controlled to ensure optimal crop growth and quality. Any malfunction or failure of these components or processes can result in crop loss or damage. For instance, a power outage can affect the artificial lighting, ventilation, irrigation, and temperature control of a Controlled-environment agriculture facility, leading to stress or death of the plants. Similarly, a contamination or imbalance of the nutrient solution can affect the health and yield of the crops. Therefore, Controlled-environment agriculture systems require skilled and trained personnel to operate and maintain them, as well as backup systems and contingency plans to deal with emergencies. A third challenge of Controlled-environment agriculture is the social acceptance and perception of the consumers and the public. Controlled-environment agriculture systems are often seen as unnatural or artificial ways of growing food that may compromise its taste, nutrition, or safety. Some consumers may prefer organic or locally grown food that is perceived as more natural or authentic. Moreover, some critics may argue that Controlled-environment agriculture systems are not sustainable or ethical because they use more energy than conventional agriculture or displace rural farmers from their livelihoods. Therefore, Controlled-environment agriculture systems need to communicate their benefits and values to the consumers and the public, as well as address their concerns and expectations.

Artificial Intelligence and Robotics

Two cutting-edge technologies, artificial intelligence (AI) and robotics, have the potential to revolutionize the agricultural industry. Artificial intelligence is the capacity of machines to carry out operations like learning, reasoning, and making decisions that call for human intelligence. The area of engineering known as robotics is concerned with the creation, maintenance, and use of robots that can carry out physical tasks. Robotics and artificial intelligence can help farmers increase crop productivity, lessen their impact on the environment, and increase food security. Precision farming, which uses sensors, drones, satellites, or robots to gather and analyze information on crop conditions, soil quality, weather, pests, and diseases, is one of the applications of AI and robotics in agriculture. With the aid of this information, farmers can better utilize inputs like seeds, water, fertilizer, pesticides, and fertilizer while also adjusting their management techniques to the unique requirements of each crop and field. Precision farming can boost yields, cut costs, and lessen harm to the environment (Datamation, 2022). Vertical farming, which involves growing crops in stacked layers indoors or in urban areas, is another way that artificial intelligence and robotics are being used in agriculture. AI algorithms can be used in vertical farming to manage each crop layer's ideal lighting, temperature, humidity, and nutrient levels. Automating processes like planting and harvesting is another way that vertical farming can use robots.

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Together, Artificial intelligence and robotics can help farmers improve crop productivity, reduce environmental impact, and enhance food security. One of the main benefits of Artificial intelligence and robotics in agriculture is precision farming, which involves using sensors, drones, satellites, or robots to collect and analyze data on crop conditions, soil quality, weather, pests, diseases, and weeds. This data can then be used to optimize crop management practices, such as irrigation, fertilization, pest control, harvesting, and post-harvest processing. Precision farming can increase crop yields, reduce input costs, save water and energy, and minimize chemical use and greenhouse gas emissions (Datamation 2022). Another benefit of Artificial intelligence and robotics in agriculture is vertical farming, which involves growing crops in stacked layers indoors or in urban areas. Vertical farming can use Artificial intelligence algorithms to create optimal light and water conditions for different crops, and robots to automate planting, harvesting, and packaging. Vertical farming can produce more food per unit area than conventional farming, reduce land use and deforestation, and shorten the supply chain from farm to fork (Harvard International Review 2020).

However, Artificial intelligence and robotics in agriculture also pose some challenges and risks that need to be anticipated and addressed. One of the challenges is the high cost of acquiring, maintaining, and upgrading Artificial intelligence and robotics systems, which may limit their accessibility and affordability for smallholder farmers and developing countries (Senyolo et al., 2018). Another challenge is the ethical and social implications of replacing human labor with machines, which may affect employment opportunities, income distribution, rural livelihoods, and cultural values. A third challenge is the cyber-security and safety issues of Artificial intelligence and robotics systems, which may be vulnerable to hacking, malfunctioning, or misuse. Therefore, Artificial intelligence and robotics in agriculture require a balanced approach that considers both the opportunities and the challenges of these technologies. To achieve this, there is a need for more research and innovation to develop cost-effective, reliable, and user-friendly Artificial intelligence and robotics solutions for different agricultural contexts. There is also a need for more regulation and governance to ensure ethical, responsible, and inclusive use of Artificial intelligence and robotics in agriculture. Moreover, there is a need for more education and training to equip farmers with the skills and knowledge to adopt and benefit from AI and robotics in agriculture.

Biotechnology

In the field of biotechnology for agriculture, living organisms—plants, animals, and microorganisms—are modified using a variety of scientific techniques, including genetic engineering, molecular markers, molecular diagnostics, vaccines, and tissue culture (Wikipedia, 2021). Using selective breeding, biotechnology has been used in agriculture for centuries to improve desired traits in plants and animals. However, developments in molecular biology over the past few decades have made it possible to transfer genes between organisms that are more distantly related, leading to the creation of transgenic or genetically modified organisms. This technology has the potential to boost crop productivity, enhance nutrient quality, and confer resistance to pests, diseases, and environmental stresses (Vedantu, 2021). Some of the techniques used in biotechnology in agriculture are:

Genetic engineering / rDNA technology: This technique involves the deliberate modification of one or more genes in an organism using recombinant DNA (rDNA) technology, which allows the transfer of genes across different species. This can result in transgenic crops

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that possess desirable traits such as improved yield, flavor, color, growth rate, or herbicide tolerance

- Tissue culture: This technique involves the cultivation of plant or animal tissue fragments in a controlled environment where they can survive and grow. This can help in the propagation of plants that are difficult to breed by conventional methods, such as orchids or bananas, or the preservation of endangered or rare species.
- Embryo rescue: This technique involves the isolation and nurturing of an immature embryo in a controlled environment to ensure its survival. This can help in the production of hybrid plants that are otherwise incompatible due to cross-pollination barriers, such as wheat and rye.
- Molecular diagnostics: This technique involves the use of molecular tools such as DNA probes or PCR to detect and identify pathogens or pests that affect crops. This can help in the diagnosis and management of diseases and pests, as well as the development of resistant varieties.
- Vaccines: This technique involves the use of biotechnology to produce vaccines that can protect animals or plants from diseases. For example, edible vaccines can be produced by genetically engineering plants to express antigens that can induce immunity in animals or humans who consume them

One of the main benefits of biotechnology in agriculture is that it can enhance crop yields and quality by introducing genes that confer desirable traits such as drought tolerance, herbicide tolerance, insect resistance, or enhanced nutritional value (Yoon et al., 2021). For example, scientists have developed drought-resistant crops by inserting genes from bacteria that produce a protein that helps plants retain water. These crops can grow in unfavorable conditions and different types of soil, which could help countries that suffer from water scarcity and food insecurity. Another example is the development of golden rice, which contains genes from daffodils and bacteria that produce beta-carotene, a precursor of vitamin A. This rice could help prevent vitamin A deficiency, which affects millions of children and pregnant women in developing countries and can cause blindness and increased susceptibility to infections. Another benefit of biotechnology in agriculture is that it can reduce the use of pesticides and fertilizers by creating crops that are resistant to pests and diseases or that can fix nitrogen from the air. For instance, scientists have developed crops that contain genes from a soil bacterium called Bacillus thuringiensis (Bt), which produces a toxin that kills certain insects. These crops can reduce the need for spraying insecticides, which can have harmful effects on human health and the environment. Similarly, scientists have developed crops that contain genes from a bacterium called Agrobacterium tumefaciens, which enables plants to produce their own nitrogen fertilizer. These crops can reduce the dependence on synthetic fertilizers, which can contribute to soil degradation, water pollution, and greenhouse gas emissions.

However, biotechnology in agriculture also has several drawbacks and risks that need to be carefully assessed and managed. One of the main challenges is ensuring the safety and quality of genetically engineered foods for human consumption. There are concerns that transgenic foods may cause allergic reactions, toxicity, or gene transfer to human cells or gut bacteria (Glover et al., 2019). There are also questions about the long-term effects of consuming foods that contain novel proteins or nutrients that are not normally present in conventional foods. Moreover, there are issues related to the labeling and regulation of genetically engineered foods, as different countries have different standards and policies regarding their approval and marketing. Another challenge is protecting the environment and biodiversity from the potential impacts of biotechnology in agriculture. There are fears that transgenic crops may cross-pollinate with wild relatives or non-transgenic crops, creating unwanted hybrids or gene flow. This could result in the loss of genetic diversity, which is essential for maintaining the resilience and adaptability of natural ecosystems. There are also worries that transgenic crops may harm non-target organisms or disrupt ecological interactions by creating new pests or weeds, altering food

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webs, or affecting soil microorganisms. Furthermore, there are concerns that transgenic crops may reduce farmers' choices and diversity by creating dependency on multinational corporations that own the patents and seeds of these crops.

CONCLUSION

This paper has reviewed the literature on how technological innovation can enhance sustainability practice in the agricultural sector. The main findings are:

1. Technological innovation can improve the productivity, efficiency, and resilience of agricultural systems, while reducing the environmental and social impacts of farming activities.
2. Technological innovation can also enable new forms of agriculture, such as vertical farming, precision agriculture, and biotechnology, that can address the challenges of food security, climate change, and resource scarcity.
3. Technological innovation can foster a transition to a circular economy in agriculture, where waste is minimized and resources are reused or recycled, creating value-added products and services.
4. Technological innovation can facilitate the participation and empowerment of farmers and other stakeholders in the agricultural value chain, through digital platforms, data sharing, and co-creation processes.

However, the literature also identifies some barriers and risks that may hinder or limit the adoption and diffusion of technological innovation in agriculture. These include:

1. The lack of adequate infrastructure, skills, and finance to support the development and implementation of technological innovation in rural areas.
2. The potential negative effects of technological innovation on biodiversity, human health, and social equity, especially if not regulated or governed properly.
3. The possible trade-offs and conflicts between different dimensions of sustainability, such as economic growth versus environmental protection, or efficiency versus diversity.
4. The uncertainty and complexity of the impacts and outcomes of technological innovation in agriculture, which may vary depending on the context, scale, and time frame.

POLICY RECOMMENDATION

Technological innovation can enhance sustainability practice in the agricultural sector by increasing productivity, reducing environmental impact, and improving social and economic outcomes. However, to achieve these benefits, there are several challenges and opportunities that need to be addressed by both industry and academia. Some policy recommendations for fostering technological innovation and sustainability in agriculture include:

1. Industry should invest in research and development (R&D) of new technologies that can improve crop yield, quality, and resilience, such as precision agriculture, biotechnology, and digital platforms. Industry should also collaborate with academia and other stakeholders to ensure that the technologies are aligned with the needs and preferences of farmers and consumers, as well as the environmental and ethical standards of society.
2. Academia should conduct interdisciplinary and trans-disciplinary research that can provide evidence-based insights and solutions for the complex and interrelated issues of sustainability in agriculture. Academia should also engage with industry and other stakeholders to facilitate the transfer and

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adoption of new technologies, as well as to monitor and evaluate their impacts on the triple bottom line of people, planet, and profit.

3. Both industry and academia should promote education and training programs that can enhance the skills and competencies of farmers and other agricultural workers in using new technologies and implementing sustainability practices. Both industry and academia should also foster a culture of innovation and sustainability that can encourage creativity, collaboration, and continuous improvement among all actors in the agricultural sector.
4. The need for a holistic and systemic approach to assess and evaluate the sustainability performance of technological innovation in agriculture, taking into account the multiple dimensions, indicators, and stakeholders involved.
5. The importance of fostering a culture of innovation and learning in the agricultural sector, through education, training, and capacity building programs for farmers and other actors.
6. The role of policy makers and regulators in creating an enabling environment for technological innovation in agriculture, by providing incentives, standards, and guidelines that balance the benefits and risks of new technologies.
7. The opportunity for collaboration and co-innovation among different sectors and disciplines, such as academia, industry, government, civil society, and consumers, to address the complex and interrelated challenges of sustainable agriculture.

SUGGESTION FOR FURTHER STUDY

This study explored how technological innovation can enhance sustainability practice in the agricultural sector. It reviewed the current state of agricultural productivity and innovation, and identified some of the key challenges and opportunities for improving environmental performance and resilience. It also examined some of the emerging technologies and techniques that can help farmers and agri-food firms adopt more sustainable and efficient production methods. The study concluded with some policy recommendations for fostering a more conducive and supportive innovation system for agriculture. Some possible suggestions for further study on this topic include:

1. Conducting comparative case studies of different countries or regions that have successfully implemented or adopted green technologies and techniques in agriculture, such as renewable energy, zero tillage, biotechnology, organic farming, vertical farming, irrigation, integrated pest management, drones, fleet management, and digital sensors. These case studies could provide valuable insights and lessons learned for other contexts and stakeholders.
2. Developing indicators and metrics to measure and monitor the impacts of technological innovation on sustainability practice in agriculture, such as total factor productivity, greenhouse gas emissions, water use efficiency, soil health, biodiversity, animal welfare, food quality and safety, and social and economic benefits. These indicators and metrics could help evaluate the effectiveness and trade-offs of different technologies and techniques, and inform decision making and policy design.
3. Exploring the ethical and societal implications of technological innovation in agriculture, such as the acceptability and regulation of genetically modified organisms (GMOs), the ownership and governance of data and information, the distribution of costs and benefits among different actors and groups, and the potential risks and uncertainties associated with new technologies. These implications could have significant effects on the adoption and diffusion of technological innovation in agriculture, as well as on its sustainability outcomes.

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