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Review Article

Emerging Innovations in Agriculture and Resource Management: A Multidisciplinary Perspective

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Abstract

The main strategic goal of creative agronomic research in the upcoming decades should be the intensification of sustainable crop production. Crop production can be intensified in terms of higher output and productivity (efficiency) while also strengthening sustainability using a variety of farming practices, approaches, and technologies that are frequently highly location-specific. Encouraging farmers to employ environmentally suitable technologies and techniques and ensuring that farmers are increasingly adopting, utilizing, and innovating sustainable agriculture practices are the primary challenges. Integrating farmers' local knowledge with formal knowledge based on science has a significant yet untapped potential. This integration aims to develop better practices and technological possibilities through beneficial institutional frameworks to support an innovation system. This also holds true for the design, implementation, and supervision of improved natural resource management that links local initiatives to new outside expertise. The different stages of the innovation system, such as technological adoption, adaptation, and diffusion at the farm level, should also be thoroughly measured. Additionally, the impact of agricultural policies on technical efficiency, technological change, and production intensification should be investigated. This study examines management techniques that support intensification and sustainable crop production systems in addition to attesting to improvements in crop and cultivar selection. Additionally, crop farming systems using a primarily ecosystem approach are described in the paper, along with the scientific application of this technique for controlling weed and insect populations. It also discusses the advantages and disadvantages of irrigation methods and examines the advancements in fertilizer and nutrient management, which form the cornerstone of productivity increase. Lastly, it offers a course of action based on seven shifts in agricultural development that emphasize the necessity of analyzing how innovation takes place in the agricultural industry.

1. Introduction

The world's population has grown by more than 4 billion over the past 40 years, and it is predicted to rise from an estimated 7 billion in 2011 to around 9.1 billion in 2050 over the next 40 years. The region of the world that makes up today's developing nations will account for almost all of this population growth, while the least developed nations are predicted to see the largest relative population rise (120%). For at least 40 years to come, the world's need for food will rise due to this continuously expanding population. Agricultural production must rise by 70% worldwide and by nearly 100% in order to fulfil the increased demand for food, excluding the additional need for agricultural products used as feedstock in the production of biofuels. In the past, expanding agricultural areas and taking advantage of new fish sources

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were the main ways to address food shortages. Growing competition for land, water, and energy, as well as the pressing need to lessen the food system's environmental effect will have an impact on our capacity to produce food in the future. Food security is further threatened by the consequences of climate change [1]. There is an imbalance in the supply and demand of resources. However, despite the fact that grain production has more than doubled over the past 50 years, just 9% more land has been used for arable agriculture worldwide. Even though the population has doubled over the past 50 years, there has been a noticeable increase in food production, which has significantly reduced the percentage of individuals who are either seasonally or chronically hungry. Formerly viable agricultural land has been lost in recent decades due to urbanisation, other human uses, desertification, salinisation, soil erosion, and other effects of unsustainable land management. There will probably be further losses to the natural resource basis of agriculture, particularly water loss, which could be made worse by climate change [2]. Competitive pressures have increased as a result of recent policy initiatives to develop first-generation biofuels on high-quality agricultural land [3]. Increasing productivity is hence the task of boosting food production, food security, and farmer revenue.

The shift in output/input ratios over time is referred to as productivity growth. As a result, it serves as an indicator of resource efficiency per unit of output. However, enhanced genetic resources, higher use of pesticides, increased intake of agricultural mineral fertilisers, increased use of fossil fuel and mechanised farm power, and increased irrigation intensity have all contributed significantly to productivity growth during the past 40 years.

The requirement for profitable and productive agriculture that both preserves and enhances the environment and natural resource base while simultaneously favourably supporting the use of environmental services is recognised by the emerging paradigms of sustainable crop production intensification. Sustainable crop production intensification must reduce emissions and encourage soil carbon storage in order to mitigate the causes of climate change as well as its effects on agricultural productivity. Intensification should boost biodiversity in crop production systems, both above and below ground, to enhance ecosystem services for higher productivity and a healthier environment.

Information and communication technologies (ICTs) are regarded as instruments that boost businesses' and manufacturing units' competitiveness and productivity. As ICTs are used and adopted more widely, these advantages expand [2]. In a similar vein, agricultural businesses are under pressure to implement ICTs because of safety and quality standards. Businesses are being forced to compete in regional and local marketplaces with set standards for traded goods as consumers adopt models similar to those in industrialised nations [3]. Thus, it is essential to put into practice policies that promote economic development and expansion in tropical agricultural areas. Despite difficulties brought on by soil composition [4] and climate circumstances [5], these areas supply the food that the world's population needs. ICTs, which include a variety of tools and services that help farmers gather, store, analyse, and share information, are one of these tactics. In many aspects, these technologies enable access to services like drones for comprehensive aerial images, mobile banking, and satellite-provided current weather forecasts [6].

In developing countries, information and communication technologies (ICTs) are essential because they present chances for international integration. They improve access to more reasonably priced connectivity, particularly broadband availability, change how basic services are provided, spur productivity development and innovation, and boost competitiveness. However, in order to reduce the effects of overuse of agrochemicals, especially insecticides [7], fertilisers [8], and herbicides [9], it is crucial to guarantee the best possible management of soil and water resources. Production systems are moving toward precision agriculture [10], which is turning into smart agriculture, in order to increase the efficiency of natural resource management in agricultural output. This strategy depends on technical advancements that make it possible to handle enormous volumes of data for decision-making while applying herbicides, insecticides, and fertilisers. The most popular tools for managing soil and water are based on artificial intelligence, machine learning [11], drones [12], mobile apps [13], and the Internet of Things [14].

All objectives may be accomplished through a set of soil-crop-nutrient-water-landscape system management techniques called Conservation Agriculture (CA) [15]. CA has the potential to manage declining soil productivity and to enhance the base of natural resources and resource-use efficiency. As a result, it reduces production costs by adapting to and mitigating climate change and making better use of resources. To increase profitability and the security of farmers' livelihoods, integrated farming systems based on CA must produce more for less, regardless of location, management, or socioeconomic circumstances.

2. The Purpose of Modern Technology

Future technological innovation and quick advancement will have a big impact on agricultural output and stability. It is anticipated that emerging technology will give farmers and other stakeholders vital information and resources to improve decision-making across the whole food production process. These developments, which range from precision agriculture to sophisticated data analytics, will make it possible to make better decisions, maximize resource utilization, and increase crop yields. For example, farmers can increase efficiency and decrease waste by using real-time data on crop growth, weather, and soil health to make timely adjustments [16]. The 475 million small farms in the world are especially affected by the creation and application of new agricultural technologies. These farms, which make up a sizable share of the world's agricultural production, stand to gain greatly from technological developments. Innovations like mobile apps, automated systems, and inexpensive sensors can help smallholders run their businesses more efficiently, increasing output and profitability. Additionally, technology can make it easier for small-scale farmers to obtain supply chain management tools and market data, enabling them to compete in international marketplaces [17]. The efficiency and sustainability of the agricultural industry have undergone a sea change because to innovations centred on precision agriculture and the extensive use of ICTs. According to the reviewed studies, automation of agricultural operations has led to considerable time savings and improved accuracy in the application of resources such as fertiliser, insecticides, and herbicides [18]. Furthermore, the use of digital techniques, such as machine learning, has broadened agriculture's focus beyond productivity, tackling important environmental issues like water quality and climate change [19]. As demonstrated by particular instances from nations like Ecuador, the use of ICTs in agriculture has promoted innovation and knowledge management, optimising the management of natural resources and raising the caliber of finished goods.

Agriculture has benefited greatly from technological advancements, particularly the Internet of Things (IoT) and the use of drones, which have made it possible to anticipate and adjust to changes in microclimates and to gather data more precisely and effectively. These new technologies are essential for addressing climate change issues and guaranteeing the sector's sustainable growth in addition to increasing agricultural output and effective information management [20]. In example, drones have transformed data collection, making it possible to monitor agricultural conditions more precisely and frequently, which lowers costs and improves crop management [21]. When taken as a whole, these technologies offer creative approaches to resource management and environmental issue adaptation, marking a significant shift in agriculture. ICT integration in water management is essential for enhancing access to vital information and boosting involvement in environmental decision-making. The problems associated with the depletion of high-quality water supplies have been successfully addressed by digital tools, particularly in irrigation and drinking water management. In addition to optimising data collection in agriculture, advances in hardware and software also make it easier to manage a sufficient water balance for crops, underscoring its significance in terms of scalability and adaptability to the sector's future requirements [22]. Agricultural planning and watershed management have greatly benefited from the application of machine learning in fields including early warning, mapping, and remote sensing [20]. These techniques have made it possible to analyze and simulate hydrometeorological data effectively, which is essential for sustainable water management. Furthermore, controlled irrigation system management via the Internet of Things (IoT) and the application of big data and machine learning have been shown to be crucial for more effective and ecologically sustainable water management, lowering costs and guaranteeing water quality for human consumption [20, 23].

Emerging technologies like big data and machine intelligence are revolutionising hydrology and environmental studies. Hybrid machine learning methods, like those based on decision trees, have improved the accuracy of short-term water quality prediction [24]. This accuracy is essential for effective resource management when water is limited. Furthermore, by integrating these technologies with advanced sensors and complex agrometeorological networks, real-time data collection and analysis are made possible, allowing for accurate and knowledgeable judgments in agriculture and water management. Soil management in agriculture has been transformed by the introduction of digital instruments, particularly artificial intelligence (AI). The planning and management of natural resources in open field and greenhouse agriculture has been made easier by these technologies, which have made regulated and effective access to information possible. The study of processes like desertification has been greatly impacted by developments in deep learning (DL) and machine learning (ML), which offer a more global and interdisciplinary perspective [25]. AI has also shown itself to be essential in the development of agricultural policies, recognising regions with agricultural potential and figuring out the best ways to maintain soil adaptability and advance sustainable agriculture [26]. Efficiency in areas like soil moisture, infiltration, and erosion has greatly increased with the use of hybrid intelligent models in soil management. The accuracy of estimating important factors like soil organic carbon variability and erosion susceptibility has increased thanks to these models, which incorporate cutting-edge AI techniques, including artificial neural networks, support vector machines, and cubistic regression [27]. The usefulness of these technologies in sustainable soil management is further highlighted by the use of AI in the exploration of remediation techniques, which helps to remediate polluted soils while lowering costs and limiting environmental impact [28, 29]. By offering user-friendly, configurable interfaces that adjust to different agroecosystems, mobile applications and artificial intelligence (AI) technologies are transforming fertilizer dosing in agriculture [30, 31]. A machine learning-based recommendation system can be created using this information [32]. In addition to making data management and collection easier, these tools help enhance resource efficiency and lessen pollution in the environment. These apps' capacity to interface with neural networks and adjust to soil fluctuations greatly boosts yields and profitability while enhancing environmental sustainability.

When AI and machine learning systems are combined in agriculture, important insights are obtained to maximise agricultural choices. Accurate fertilizer type and quantity recommendations are made possible by algorithm-based systems such as random forests and support vector machines, which increase production and reduce environmental impact [16]. The improved control of soil nutrients made possible by these technological developments promotes soil fertility and long-term sustainability. An important development in precision agriculture is the use of machine learning models into intelligent fertilization systems [33]. These methods offer effective resource management under limited soil and environmental circumstances in addition to improving agricultural yield forecasts. The use of AI based on (NPK) spectroscopy in hydroponic systems and greenhouses demonstrates how technology can boost agricultural yield in compact areas, hence resolving issues with contemporary agriculture [34]. Agrochemical management is changing as a result of technological advancements in agriculture, particularly the deployment of artificial intelligence (AI) and intelligent sensing and application systems. By enabling more accurate and targeted dosage of herbicides and other goods, these technologies greatly lower the dangers and misuse of agrochemicals [15]. Modern weed detection systems and variable rate sprayers, such as the VGG-16 model, have been shown to be successful in cutting expenses, lowering the dangers of environmental pollution, and encouraging more environmentally friendly and health-conscious farming methods.

Precision agriculture has advanced significantly with the use of drones in pesticide applications, which has both economic and environmental benefits. Drones minimise environmental effect, save time and money, and use less water and pesticides despite their high initial investment cost [16]. The effectiveness of these systems in a range of agricultural settings, from small holdings to big farms, is confirmed by experimental results. An essential step toward more sustainable and ethical farming methods is their capacity to apply items precisely and effectively, which lowers management expenses and lessens the impact on the environment.

3. Technologies and Techniques

3.1. Renewable Energy

Because renewable energy can regenerate itself, we can rely on it for a long period without totally depleting it, making it a great alternative to non-renewable fossil fuels. Because renewable energy sources don't emit dangerous emissions into the atmosphere, using them is also better for the environment. Water pumps, lighting, and farm equipment can all be powered by solar energy. Furthermore, solar thermal technology can be utilised for subterranean soil heating, water heating, and solar greenhouses. Water can be pumped for irrigation using wind turbines, which require very little land. Burning biomass, which includes plant and animal waste, can produce energy and heat for dairy operations, crop drying, and building heating [4].

3.2. Biotechnology

The creation of genetically modified (GM) crops with better characteristics, such as higher resistance to pests and drought, increased yield, and increased tolerance to environmental challenges, is included in biotechnology. These developments may result in the development of high-yielding cultivars that use less water, inputs, and ploughing, increasing agricultural sustainability and efficiency. Additionally, biotechnology contributes to resource saving and increased climate change resistance by making it easier to produce bio-pesticides and other advantageous agricultural products [31]. Despite these benefits, there is a lot of controversy and discussion around biotechnology. The safety of GM crops for human health, animal welfare, and the environment is frequently the main point of concern. The discussion is further complicated by the possibility of abuse, such as producing crops with unexpected outcomes or adding to ecological imbalances. To solve these problems and guarantee that biotechnology is used sensibly and morally, strict safety evaluations and legal frameworks are necessary. It is critical to weigh the potential advantages of biotechnology against its dangers and ramifications as it develops [31].

3.3. Precision Agriculture and Technologies

Using the appropriate technologies to boost crop output, efficiency, profitability, and productivity is the foundation of precision agriculture [32]. Computational technology is employed in conjunction with remote sensing advancements and geographic location devices to address the ambiguity of the environment. The application of environmental modelling and risk management algorithms will result in the most efficient use of resources. Compared to traditional technology, precision technology can assess crop conditions considerably more quickly, and harvesting or input application technology can react quickly to changing environmental circumstances, decreasing waste. In order to better understand crops and make plans that would maximise their harvests, farmers have access to scientific data. One piece of equipment used in precision agriculture is the drone. Farmers will have a better understanding of the health of their crops and their needs for water and nutrients since they can obtain an overview of the farm more quickly than with conventional methods. By spotting issues that would be challenging to find otherwise and acting promptly to stop insect infestations or disease outbreaks, they will also be able to save money. Although there are many applications for drones in agriculture, their main function is to gather detailed data using various sensors, such as remote sensing technologies. Sensors can be used to track animal movements, pH levels, and microclimate data. The information gathered can be used to create 3D models and maps of a region, which can then be further examined to determine crop health, identify crop disease stress, and identify irrigation problems. Drones can spray agrochemicals, plant seeds, and spread mulch [21]. There are several uses for drones, such as mapping irrigation systems and managing livestock. Drones come in two varieties: multi-copter and fixed-wing models. Fixed-wing drones can stay in the air longer and are made to endure severe weather. They are more expensive, though, because they need a lot of room to take off and land. Multi-copter drones can be used for photogrammetry and precise pesticide, fertiliser, and seeding spraying. They are also more adaptable, simpler to fly, and less expensive.

3.4. Robotic Automation

Robotic harvesters, self-driving tractors, and automated watering and sowing robots are all products of robotics innovation. Despite the fact that these technologies are still relatively new, many traditional agricultural businesses have incorporated them at a respectable rate. Instead of randomly spraying pesticides from a tractor, automated equipment can be utilised to apply them in a targeted manner. In addition to improving worker health by reducing pesticide exposure, this will lessen soil compaction and, consequently, runoff because there are no human passengers, making the machinery lighter. In order to address issues like the lack of agricultural labour, shifting customer preferences, and even the environmental effects of farming, automation technology attempts to handle simpler, routine, and repetitive jobs [22].

3.5. Technology Used in Livestock Farming

Maintaining accurate financial records, overseeing employees, and making sure the animals are properly cared for and fed are all part of managing livestock, such as poultry, dairy cows, or cattle. However, improvements in digital technology, genetics, and nutrition have made managing livestock easier and more effective. For example, sensors, such as electronic ear tags, can be used to monitor daily activity and health-related problems in cattle, giving the herd as a whole useful information. Producers may assess the genetic risks of their herds and forecast future profitability with the aid of an understanding of genomics. Additionally, workers now have more flexible work schedules and better cow welfare thanks to automated robotic milking equipment. These technologies have the potential to improve livestock management, welfare, and productivity [27].

3.6. Monitoring Irrigation and Water Management

Water may be captured, stored, and transmitted with the least amount of waste and pollution possible thanks to technology. To cut down on excessive water use and stop river depletion, dry land, and soil deterioration, farmers might cultivate local crops. Recycled wastewater can be utilised for irrigation, while rainwater collection technologies can retain rainwater during dry spells. Other water-saving technologies include wireless and remote monitoring systems, which give farmers more control over their operations, and precision technologies like drones, which encourage more effective use of resources [18]. One of the biggest hazards to society and the economy in the upcoming years, according to the World Economic Forum, is the water problem. As a result, it is essential to use and manage water resources wisely both now and, in the future, with an emphasis on agriculture, which is one of the world's biggest water user industries. In order to achieve secure water and increase field productivity while lowering expenses through the use of intelligent water management and monitoring techniques, water management and monitoring in agricultural activities are crucial.

Conventional irrigation techniques, including overhead sprinklers or flood irrigation, can be ineffective and wasteful. Through evaporation, runoff, and deep percolation, they cause water loss. However, by enabling accurate and efficient irrigation techniques, contemporary water management technology has completely changed how farmers use water. The use of sensors and data analytics is one of the most significant developments in water management technology. Real-time data on temperature, humidity, soil moisture, and other variables can be gathered by weather stations, soil moisture sensors, and other Internet of Things devices. Farmers may make educated decisions about when, where, and how much to irrigate by analyzing this data to gain important insights into crop water requirements [8, 19]. In order to accomplish water management using emerging technologies, monitoring devices are used to determine a number of characteristics. These include soil moisture to determine moisture patterns and water retention, rainfall to prevent overwatering and conserve resources, evapotranspiration (ET) to calculate ET with temperature/RH, wind and solar radiation data, temperature and relative humidity, wind speed and direction to predict weather patterns or determine safe pesticide application, solar radiation to understand the impact of light levels, site evaluation, plant growth, and water level to monitor water level in storage tanks and reservoirs [35]. Increased crop output and decreased crop insufficiency risk are two advantages of developing innovative irrigation water management and monitoring technology. Improved water management and monitoring reduce the need for excessive irrigation to prevent potential field flooding, lower groundwater nitrate levels, and save labor expenses. These technologies improve water quality by just applying the necessary amount of fertilizer [20].

3.7. Information Technology

In Climate Risk Management (CRM), early warning systems and weather forecasts are available at different scales and play a major role in identifying pertinent climate threats. Agriculture is significantly impacted by weather changes, and having a clear understanding of these changes helps in forecasting and decision-making that is more precise and efficient [26]. Through strategic risk management, farmers can obtain weather forecasts for up to six weeks by tracking or predicting the time and probability of variations in rainfall patterns and environmental temperature swings. Another piece of technology that helps farmers better understand weather changes is mobile phones. Mobile phones have made it easier for farmers to communicate with each other, exchange information, and get timely information about weather, market dynamics, and problem-solving strategies. AI technology can help farmers better analyze the data gathered by distant sensors, satellites, and unmanned aerial vehicles (UAVs). Algorithms that process data and adjust in response to new information are used to do this. Farmers can maximize their crop yields by using the algorithm's increasingly precise forecasts as more data is gathered.

To increase farm vehicle productivity and profitability, fleet management uses GIS technology to monitor fuel use, engine speed, maintenance plans, and other factors. Blockchain technology can help the food industry solve a number of problems, such as supply chain inefficiencies, fraud, safety recalls, and traceability. Blockchain encourages transparency and verifiable goods and procedures by monitoring ownership records and guaranteeing tamper resistance. In order to safeguard public health, it is crucial to promptly determine the cause of foodborne infections due to the perishable nature of food [14]. Blockchain replaces the inaccurate paper-based tracking approach by enabling real-time tracking of food products' transit. Additionally, by balancing prices based on data from the whole value chain, blockchain's creation of a ledger network generates market value. Blockchain offers a promising future for a more reliable and secure food trade due to its potential to improve transparency and safety [6, 7, 36].

3.8. Nanotechnology

The study and manipulation of materials with sizes between 1 and 100 nm, as well as their effects on human health, are all part of the area of nanotechnology. Increased crop productivity can be achieved by using nanotechnology to design crops that can resist a variety of weather conditions, detect and control plant diseases, and improve their capacity to absorb nutrients from the soil [8]. To further its uses, native technologies could be integrated with nanoscale biomaterials. Producing crops that can withstand high temperatures, creating nanotubes that store rainwater in the soil so plants may use it during droughts, and developing specialised poisons for certain insects known as nano-pesticides are all possible using nanotechnology [6]. By focusing on pathogens, nanoparticles can be utilised to monitor and treat food crop illnesses. Carbon, silver, silica, and alumina silicate nanoparticles can be used to do this [1]. To regulate nutrient release into soils and stop nutrient loss, nano-fertilizers can be created. Nutrients can be given as emulsions or captured by nanomaterials covered with a thin layer. Surfactants, organic polymers, and mineral nanoparticles are among the different kinds of nanoparticles used in the production of nano-pesticides. These nano-pesticides are made to target specific insects without harming other significant insects. Plant infections require quick and sensitive sensors, and nanosensors can track agroclimatic conditions and incorporate into a nanosystem that releases pesticides and fertilizers when necessary. The cost-effectiveness of nanotechnology makes it a promising technology with numerous applications for sustainable agriculture.

3.9. Greenhouse Technology

By using cutting-edge technology like LED lights and automated control systems to customize the production environment according to individual needs, small-scale greenhouses are evolving into larger-scale establishments. The industry is seeing an increase in capital investment due to the growing popularity of urban greenhouses for local food production. The primary crop grown for Christmas in November and December is poinsettias. The leaves progressively change from green to scarlet by artificially creating longer nights. Additionally, Gerbra grows year-round in response to shifting environmental conditions. a hydroponic farm that grows some vegetable crops and leafy vegetables in greenhouses. Generally speaking, hydroponics consumes more electricity than many other greenhouse production techniques. It uses fewer scarce resources, such as water, fertilizer, arable land, and pesticides, although consuming more energy than conventional vegetable and herb growing.

4. Conclusion

Through advantageous multi-stakeholder institutional arrangements that can support innovation systems, there is a vast yet underutilized potential to connect farmers' local knowledge with science-based breakthroughs. This also applies to the planning, execution, and oversight of enhanced natural resource management that connects local efforts with outside knowledge. The context of agricultural development is becoming more globalized. Future research should therefore focus more on the institutional arrangements in agricultural innovation and knowledge systems, as well as the responsibilities that the public and private sectors play in bolstering innovation systems and promoting the adoption of new technologies. Some actions to be taken in this regard are: existence of cross-sector research collaboration, knowledge transfer, and intellectual property rights protection. A thorough effort should be made to measure the many stages of the innovation system, such as by evaluating its technological acceptance and diffusion at the farm level, and to look into how agricultural policies affect technical efficiency and technological development. Low-disturbance agro-ecological systems, where production technologies and practices are more in line with the ecosystem process and where both productivity and environmental services can be harnessed, are replacing high-disturbance production systems with a high environmental impact. Farmers must be an essential component of any successful innovation system, and multi-stakeholder innovation systems have a significant role to play in producing pertinent technology that farmers may embrace and modify.

Article Information

Disclaimer (Artificial Intelligence): The author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.), and text-to-image generators have been used during writing or editing of manuscripts.

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