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Influence of Science and Technology on Agricultural Production: Advances, Impacts, Challenges and Future Perspectives

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ABSTRACT

Food security and agriculture have long been closely related, but sustaining adequate food production is getting harder due to the rising demand for labour, land, water, and other resources. New methods that can help farmers increase productivity while making better use of these resources have been presented over time by scientific and technological advancements. From the Green Revolution and early farm mechanisation to the current application of biotechnology, precision farming, artificial intelligence, sensors, the Internet of Things (IoT), drones, robotics, and smart irrigation systems, agriculture has advanced. These advancements have changed how crops are grown, monitored, and controlled. While contemporary technology has made it feasible to gather field-level information and apply it to farming decisions, scientific research has helped develop new crop types and better strategies for controlling pests and diseases. When used properly, these technologies can lower the amount of work required in farming, boost crop output and quality and improve the efficiency of water and other inputs. However, not every farmer can equally benefit from them. Adoption may be hampered by the expense of equipment, insufficient infrastructure, a lack of technical expertise, poor Internet connectivity, worries about the effects on the environment and the handling of agricultural data. Therefore, resource efficiency, sustainability and affordability should all be considered when evaluating the role of science and technology in agriculture rather than just production.

Keywords: *Agricultural automation, crop management, digital agriculture, precision farming, smart irrigation .*

2. Introduction

2.1 Importance of Agriculture

Agriculture plays an important role in daily life by supplying food, raw materials, and livelihoods to a large section of the population; ensuring a sufficient food supply is therefore closely associated with food security and the well-being of communities [1]. However, agricultural production depends on several basic resources, particularly land, water and fertile soils. With the continued rise in food demand, increasing production alone cannot address the challenges agriculture faces. The resources required for farming must also be managed responsibly to ensure their continued availability. Therefore, achieving higher agricultural productivity while protecting natural resources and maintaining their long-term sustainability has become an important concern in modern agriculture [2].

Environmental conditions strongly influence agricultural production. Changes in temperature, rainfall patterns, drought and other climate-related stresses can affect crop growth and productivity. Recent reviews have highlighted climate change as an important factor affecting food production and food security, particularly because agricultural systems are directly climatic conditions. These conditions make it increasingly important to develop farming practices that can maintain production under changing environmental conditions while using water, land and other inputs efficiently [3].

2.2 Current Challenges in Agricultural Production

Agriculture currently faces several challenges that can affect the quantity, quality and reliability of agricultural production. Increasing demand for food has to be addressed alongside limited availability of productive land and freshwater resources. Climate variability can further increase production risks by affecting crop growth, water availability and the occurrence of environmental stresses. In addition, soil degradation, pests and diseases can reduce crop productivity and increase the number of inputs required for successful cultivation [4].

Labour availability and the cost of farm operations are also major concerns for agricultural producers. Many farming activities still depend on physical labour, and delays in operations such as sowing, spraying and harvesting can affect crop performance. In this context, mechanisms and automation offer practical ways to reduce manual effort and improve the efficiency of different farming operations.

They can also help farmers carry out time-sensitive activities more consistently. However, these technologies are not equally accessible to all farmers, as the initial cost of equipment and expenses involved in its maintenance can be difficult to manage [5].

2.3 Evolution of Science and Technology in Agriculture

The progress of agriculture has been closely associated with changes in scientific knowledge and the development of new technologies. In traditional farming systems, agricultural activities were largely carried out using human and animal labour and basic tools. The gradual introduction of machinery reduced the amount of physical labour required for farming and increased the speed of operations such as land preparation, planting, and harvesting. Research on smallholder farming has also reported improvements in productivity following mechanisation, although the extent of these benefits depends on factors such as access to appropriate machinery, infrastructure and other supporting resources [2].

Another important phase in the development of agriculture was the Green Revolution. During this, improved varieties were introduced alongside irrigation, synthetic fertilisers, pesticides and better crop management practises. The resulting increase in crop production showed the extent to which scientific research, when combined with suitable technological inputs, could transform agricultural productivity. At the same time, the experience of agricultural intensification showed the importance of considering environmental and socioeconomic consequences alongside productivity gains [6]. Recent research on Indian agriculture, for example, has linked the legacy of intensive agricultural development with issues such as soil and water-related problems and regional differences, while also identifying climate change as an additional challenge to agricultural systems [7].

The development of agricultural science subsequently expanded into areas such as plant biotechnology, molecular approaches to crop improvement and advanced crop-management practices. At the same time, agricultural technology moved beyond conventional machinery toward systems based on data and information. Precision agriculture introduced technologies such as GPS, remote sensing, sensors, drones and variable-rate equipment to allow crop and field conditions to be monitored more precisely.

More recently, artificial intelligence, machine learning, Internet of Things-based systems and other digital technologies have expanded the possibilities for agricultural monitoring and decision-making. These technologies can be used to collect and analyse information related to crop condition, soil characteristics, weather and agricultural inputs. As a result, modern agriculture is gradually moving from general management practices toward more site-specific and data-supported approaches [8, 9].

2.4 Aim and Scope of the Review

This review examines how science and technology have influenced agricultural production, starting from the development of agricultural mechanisation and moving towards the scientific and technological approaches used in modern farming. It discusses major advances, Internet of Things (IoT)-based systems, drones, robotics and smart irrigation. Particular attention is given to their effects on crop productivity and quality, labour requirements, resource use, and the ability of farming systems to respond to changing conditions. The difficulties associated with adopting these technologies are also considered, including high cost, unequal access, infrastructure limitations, environmental concerns and issues related to agricultural data. The review concludes by considering emerging agricultural technologies and their potential to improve productivity and resource efficiency while supporting more suitable and accessible farming systems.

3. Methodology

The review was carried out by searching scientific literature on the role of science and technology in agricultural production, with attention given to their applications, benefits, limitations and possible future developments. Relevant studies were searched mainly through Scopus, Web of Science, Google Scholar and ScienceDirect. Reports and publications from recognised organisations, particularly the Food and Agriculture Organisation of the United Nations (FAO), were also considered when they provided useful information on agricultural mechanisation, automation, digital agriculture, resource management and sustainable production. The search mainly covered publications published from January 2020 onwards to include recent developments in agricultural science and technology. Earlier studies were considered when they were useful for explaining the development of important agricultural practices and technologies.

The literature search used combinations of keywords related to agricultural production and technological development. The main terms included “agricultural production,” “agricultural productivity,” “science and technology in agriculture,” “precision agriculture,” “digital agriculture,” “smart farming,” “Agriculture 4.0,” “artificial intelligence in agriculture,” “Internet of Things in agriculture,” “agricultural robotics,” “agricultural automation,” “drones in agriculture,” “remote sensing,” “agricultural biotechnology,” “smart irrigation,” “controlled-environment agriculture,” and “sustainable agriculture.” The Boolean operators AND and OR were used in different combinations to narrow or broaden the search and identify studies related to specific agricultural technologies. This approach helped to include both established technologies and newer developments being introduced into modern farming systems.

Studies were considered eligible when they described or evaluated the application of scientific and technological approaches in agriculture and provided information related to agricultural productivity, crop management, crop quality, resource-use efficiency, labour, sustainability, resilience or production outcomes. Original research articles, review articles and systematic reviews published in peer-reviewed journals were considered. Recent reports from recognised international organisations were also included when they provided relevant information on agricultural automation, technology adoption, productivity or barriers to implementation. Particular attention was given to literature concerning precision agriculture, Internet of Things (IoT), artificial intelligence (AI), machine learning, remote sensing, agricultural drones, robotics and automation, biotechnology, smart irrigation and controlled-environment agriculture, as these technologies represent important components of modern agricultural production. Recent literature reviews have similarly examined these technologies in relation to smart farming, precision agriculture, sustainability and automation.

Publications were excluded when they were unrelated to agricultural production or did not provide sufficient information about the scientific or technological application being discussed. Duplicate publications, conference abstracts, editorials, opinion-based articles and sources lacking adequate scientific information were excluded from the main analysis. Studies that discussed a technology without establishing a meaningful connection with agricultural production, crop management, resource use or agricultural sustainability were also excluded.

The retrieved literature was screened initially according to the relevance of the title and abstract, followed by assessment of the full text of potentially relevant publications. Information from the selected literature was organised according to the major areas of scientific and technological development in agriculture, including mechanisation, agricultural biotechnology, precision agriculture, IoT, artificial intelligence, remote sensing and drones, robotics and automation, smart irrigation and controlled-environment agriculture. The findings were then compared and synthesised to examine how these technologies influence agricultural production, particularly with respect to productivity, crop quality, resource-use efficiency, labour requirements, environmental sustainability and resilience. The review also considered challenges associated with technology adoption, including economic cost, infrastructure requirements, technical skills, digital connectivity, accessibility and data-related concerns. These considerations are particularly important because although agricultural automation can improve productivity and resource efficiency, its adoption can remain difficult for small-scale producers because of financial, infrastructural and technical barriers.

The literature identification and selection process was structured in accordance with the principles of the PRISMA 2020 reporting framework. The numbers of records identified, duplicates removed, records screened, full-text articles assessed for eligibility and studies finally included will be presented in a PRISMA flow diagram (Fig. 1). PRISMA 2020 recommends transparent reporting of information sources, search strategies, eligibility criteria and the study-selection process, and recommends presenting the movement from identified records to included studies using a flow diagram where appropriate.

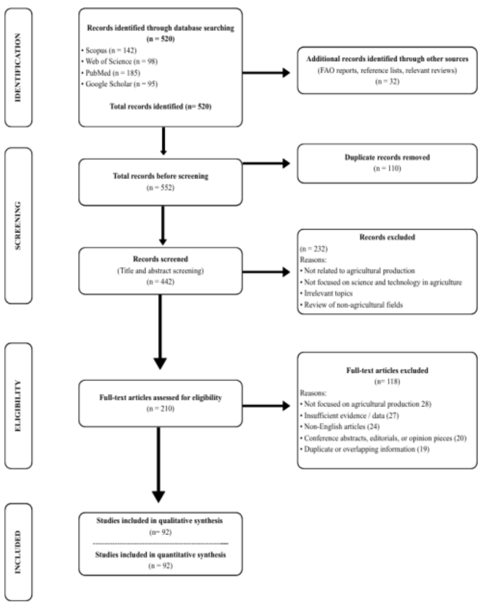

Fig. 1: Literature search and study selection process for this review are presented in the PRISMA 2020 flow diagram.

4. Historical Development of Agricultural Science and Technology

4.1 Traditional Agricultural Practices

Agricultural production initially depended mainly on human labour, animal power and simple tools developed according to local farming conditions. Farmers relied heavily on practical knowledge about soil, weather, crop seasons and seed selection, and many agricultural activities were carried out manually. Although these practices supported food production for generations, the amount of land that could be cultivated and the speed at which farming operations could be completed were largely limited by the available labour and tools. The development of improved agricultural equipment gradually reduced these limitations and marked the beginning of a more mechanised approach to farming. Recent assessments of agricultural automation describe this progression as a long-term shift from basic tools and animal power towards mechanised and, more recently, digitally controlled agricultural operations [10,11].

4.2 Agricultural Mechanisation

The introduction of mechanical power brought a major change to agricultural production. The use of tractors, power tillers, pumps, seeders, harvesters and other machines made several farm activities faster and reduced the amount of physical effort required from farmers. Mechanisation became especially useful for activities such as land preparation, planting, irrigation and harvesting, where completing the work at the right time can affect crop performance. FAO has reported that mechanisation can improve productivity, reduce physical drudgery and make better use of available labour, although these benefits are not experienced equally by all farming communities [12,13].

The use of mechanisation also differs depending on farm size, economic conditions and location. Large machines are generally more suitable for bigger and relatively uniform fields, while their use can be difficult on small or irregularly shaped farms. Studies from the Global South also show that mechanisation can provide productivity and labour benefits, but issues such as affordability, environmental effects and limited access can make it difficult for small-scale farmers to adopt these technologies [14].

4.3 Transition to Digital Agriculture

The most recent stage in this development is the movement from mechanised agriculture towards digital and data-driven farming. Precision agriculture introduced technologies such as GPS, remote sensing and field sensors to collect information about variations within agricultural fields. This was followed by the increasing use of connected devices, cloud-based systems, artificial intelligence, drones, and robotics. These technologies allow information from different sources to be collected and used to support more precise and timely decisions [15,16].

Digital agriculture is therefore different from earlier forms of mechanisation because it does not automate physical farm operations. It also supports data collection, analysis, prediction and decision-making. Technologies such as the Internet of Things, sensors, artificial intelligence, drones and robotics can work together to monitor crop and soil conditions and assist farmers in managing agricultural inputs.

The progression of agricultural technology can therefore be broadly viewed as a movement from labour-based farming to mechanised farming, followed by scientifically improved crop production, biotechnology and finally data-driven and automated agriculture. Each stage has addressed some limitations of the previous system, while also creating new challenges. This historical progression provides the basis for understanding why modern agriculture increasingly combines biological science, engineering and digital technologies rather than depending on a single technological approach [17].

5. Major Scientific and Technological Advances in Modern Agriculture

Agricultural technology has moved beyond the use of machinery alone. Modern production systems increasingly combine biological sciences, sensors, communication technologies, data analysis and automation. Technologies such as biotechnology, precision agriculture, Internet of Things, artificial intelligence, drones, robotics and smart irrigation are being used at different stages of crop production. Their importance lies in increasing production by helping farmers make decisions based on information about crop condition, soil, weather and available resources. (Fig. 2)

Fig. 2: The illustration depicts how technological advances across crop management, water use, genetics, mechanisation and digital connectivity collectively shape modern farming systems and influence productivity

5.1 Agricultural Biotechnology

Agricultural biotechnology has expanded the possibilities for improving crops beyond conventional selection and breeding. Molecular breeding, genetic engineering and genome-editing techniques can be used to modify or select traits associated with crop productivity, quality, resistance to pests and diseases, and tolerance to environmental stresses. These approaches are particularly relevant as crops are increasingly exposed to drought, salinity, temperature stress and changing pest and disease patterns [18].

One of the important developments in this area is CRISPR/Cas-based genome editing. Unlike conventional breeding, which may require several generations to combine desirable traits, genome editing allows specific genetic regions to be modified more directly. Recent research has explored CRISPR-based approaches for improving traits such as stress tolerance, disease resistance, nutritional quality and yield-related characteristics. Newer approaches, including base editing and prime editing, are also expanding the range of genetic changes that can be achieved in crop improvement [19,20].

The usefulness of biotechnology, however, depends on the crop, trait and production environment. Genome editing also requires appropriate delivery systems, reliable regeneration of edited plants and careful evaluation of unintended effects. Regulatory requirements and public acceptance remain important considerations before these technologies can be adopted on a larger scale [20].

5.2 Conventional and Advanced Crop Improvement

Crop improvement has traditionally relied on the selection and crossing of plants with desirable characteristics, and these approaches continue to form an important foundation of modern agricultural biotechnology. Conventional plant breeding involves selecting superior plants and combining useful traits through controlled crosses, followed by the evaluation and selection of promising progeny. Hybridisation and cross-breeding can bring together favourable characteristics such as higher yield, improved quality, disease resistance and tolerance to environmental stresses. Plant tissue culture has further strengthened crop improvement by providing controlled *in vitro* conditions for plant regeneration and multiplication. Techniques such as micropropagation, meristem culture, embryo rescue, anther or haploid culture, somatic hybridisation and protoplast culture can be used for rapid multiplication, conservation of valuable germplasm, elimination of pathogens and generation or selection of useful genetic variation [22-24].

Tissue culture is also important in plant genetic transformation because transformed cells must often be regenerated into complete plants under controlled culture conditions. Thus, tissue culture serves as a bridge between conventional crop improvement and newer molecular and genetic technologies. The development of molecular markers has subsequently made crop improvement more precise by allowing breeders to select plants according to genetic information in addition to visible characteristics. Marker-assisted selection can help identify plants carrying genes or genomic regions. Genomic selection uses genome-wide marker information to predict breeding performance. These approaches can reduce the time and resources required for selection and can complement conventional hybridisation and breeding methods. Consequently, modern crop improvement increasingly combines conventional breeding, tissue culture, molecular markers and genomic approaches rather than treating them as separate technologies [23].

5.3 Precision Agriculture

Precision agriculture focuses on managing agricultural fields according to the differences that exist within them rather than treating the entire field in the same way. Technologies such as GPS-guided machinery, remote sensing, geographic information systems, field sensors, drones and variable-rate technology have made it easier to collect information about soil and crop conditions and use it for more precise farm management. Remote sensing, for example, can help identify changes in crop health, soil conditions and areas affected by stress. GPS-guided machinery can improve the accuracy of activities such as planting, fertilisation and harvesting, while variable-rate technology allows fertilisers, pesticides and water to be applied according to the conditions of different parts of a field. This can help reduce unnecessary use of inputs and improve both economic and environmental efficiency [21,22,25].

One of the major benefits of precision agriculture is that it allows farmers to manage different parts of a field according to their actual requirements rather than applying the same treatment everywhere. Inputs such as water, fertilisers and crop protection products can therefore be applied according to variations within the field and the condition of the crop at a particular time.

However, the effective use of this approach depends on access to reliable field data, appropriate equipment, technical skills and the infrastructure needed to support these technologies [22].

5.4 Artificial Intelligence and Machine Learning

Artificial intelligence (AI) is becoming increasingly useful in agriculture because it can process and interpret the large amount of information collected through modern farming technologies. Machine learning and deep-learning methods can identify patterns in data obtained from soil sensors, weather records, satellite images, drones and crop-monitoring systems. These approaches are being explored for applications such as crop-yield prediction, disease identification, pest detection and decision support [26].

One of the main applications of AI is crop-yield prediction. Machine-learning and deep-learning models can use information such as rainfall, temperature, soil characteristics, humidity and vegetation indices to estimate expected crop yields. Different methods, including random forests, artificial neural networks, support-vector machines and deep-learning models, have been studied for this purpose [27].

AI is also being used to detect plant diseases. Image-based systems can examine visible symptoms and classify diseases using trained machine-learning models. Detecting a disease at an early stage may help farmers take action before it spreads across a larger area of the field. However, the accuracy of these systems depends on factors such as the quality and variety of the training data, environmental conditions and the difference between controlled images used for training and actual field conditions [26].

The integration of artificial intelligence with the Internet of Things is becoming an important area of smart agriculture. Field sensors can continuously collect information on factors Such as soil conditions, crop health, and environmental changes, while AI-based models analyse their collected data and help farmers make timely decisions. This integration, commonly described as the artificial intelligence of things, is being investigated for several agricultural applications, including yield estimation, early detection of pests and diseases and improved management of soil and water resources [25].

5.5 Agricultural Drones and Remote Sensing

Unmanned aerial vehicles, commonly known as drones, have become useful tools for collecting detailed information about agricultural fields. Equipped with cameras and other sensors, drones can capture images that help monitor crop growth, identify areas of stress and assess differences within a field. Their relatively flexible operation allows farmers and researchers to obtain field-level information at a much finer scale than may be possible through conventional field observation alone [28].

Drone-based systems have been applied to crop mapping, crop-growth monitoring, fertiliser management and the identification of areas affected by pests or diseases. Multispectral and other advanced imaging systems can provide information beyond what is visible to the human eye, which can be useful for detecting changes in vegetation and crop condition [29].

Drones can also be combined with machine-learning algorithms. Images collected from UAVs can be processed automatically to identify patterns associated with crop stress, disease or yield-related characteristics. This combination of aerial imaging and AI is becoming an important part of precision agriculture.

However, the practical use of drones is influenced by factors such as equipment cost, flight regulations, weather conditions, battery capacity, data-processing requirements and the availability of trained operators. These factors are particularly relevant when considering adoption by smallholder farmers [30].

5.6 Agricultural Robotics and Automation

Agricultural robotics represents a further step towards reducing the amount of manual work required for repetitive and labour-intensive operations. Robotic systems are being developed to assist with a range of agricultural operations including crop monitoring, weeding, spraying, planting and harvesting. Cameras, sensors and machine vision Systems are commonly incorporated into these robots so that individual plants or fruits can be identified and specific tasks can be performed with greater precision [31].

Harvesting has attracted particular interest because it often requires considerable labour and careful handling to avoid crop damage. Different robotic systems have therefore been designed using mobile platforms, robotic arms, and vision-based navigation to locate and harvest crops such as apples, strawberries, tomatoes and sweet peppers. The use of robotics for weed management is another area of active development. Machine vision technology can help distinguish weeds from crop plans allowing a robot to target weeds individually rather than applying herbicides across the whole field. This could reduce unnecessary chemical application and lessen the manual effort involved in weeding. Despite these advantages, the performance of agricultural robots can vary under actual field conditions. Changes in soil conditions, lighting, crop arrangement and weather may affect their ability to identify and handle crops accurately. The relatively high cost of robotic systems and the technical knowledge required to operate and maintain them can further limit their adoption. For this reason, in some farming environments, robots may be more useful as tools that assist farmers rather than as complete replacements for human labour [32,33].

5.7 Smart Irrigation and Water Management

The efficiency of agricultural water consumption can be directly improved by technological advancements in the field of water management. To decide which irrigation is necessary and how much water should be applied, smart irrigation systems integrate irrigation equipment with sensors and communication technologies. In certain situations, artificial intelligence. IoT-based Irrigation systems further expand these capabilities by enabling remote monitoring and control of irrigation equipment. Soil moisture sensors can show soil water status, and weather and crop requirements may also be taken into account when determining irrigation scheduling. [34].

Irrigation can be modified in response to variations in soil moisture and climatic circumstances rather than depending on a set watering schedule. This can enhance irrigation timing and minimise needless water delivery in areas with limited access to water; these devices might be especially helpful. However, several variables, like sensor accuracy, suitable irrigation design, dependable communication and adequate calibration, affect how well they work. Adoption among farmers with limited resources may potentially be hampered by the cost of installation and upkeep. [35].

5.8 Smart Greenhouses and Controlled-Environment Agriculture

Controlled-environment agriculture uses technological systems to regulate growing conditions within a defined production environment rather than relying entirely on outdoor conditions. Greenhouses and vertical farming systems can be equipped with automated controls for temperature, humidity, light, irrigation and nutrient delivery. Hydroponic, aeroponic and other soilless cultivation methods can also be integrated with sensors and digital monitoring tools to provide closer control over crop growth. More recently, artificial intelligence and IoT technologies have been explored in these systems for applications such as crop monitoring, disease detection, yield prediction, nutrient management and pesticide control. By collecting information on several environmental factors at the same time, these technologies can help growers respond more quickly to changes in growing conditions and manage the production environment more precisely [36].

Controlled-environment agriculture can be particularly useful where agricultural land or suitable outdoor conditions are limited. However, the high energy and infrastructure requirements of some systems remain important considerations. Therefore, the future development of smart greenhouses and vertical farming will depend on improving automation to make these systems more energy-efficient and economically practical.

6. Influence of Science and Technology on Agricultural Production

The influence of science and technology on agriculture can be seen in the quantity of crops produced and, in the way, agricultural resources are managed. Modern technologies can support more accurate crop monitoring, timely farm operations, better use of inputs and improved responses to pests, diseases and environmental stress. However, the extent of these benefits varies with the crop, production system, available infrastructure and the ability of farmers to adopt the technology (Table 1).

Table 1: Major technology advances transforming agricultural practices

Component of agricultural production	Major technological approaches	Major influence
Crop productivity	Precision agriculture, AI-based yield prediction, improved crop varieties	Better field-level management and improved prediction of crop performance can support higher and more stable productivity [37].
Crop quality	Biotechnology, AI-based crop monitoring, automated harvesting	Improved crop traits, early detection of stress and more consistent harvesting can help maintain product quality [39].
Water management	Smart irrigation, soil-moisture sensors, IoT	Irrigation can be adjusted according to soil and environmental conditions, helping avoid unnecessary water application [5].
Fertilizer and pesticide use	Precision agriculture, remote sensing, variable-rate technology	Inputs can be targeted to areas where they are most needed, reducing unnecessary application and improving input-use efficiency [40].
Pest and disease management	Drones, remote sensing, machine learning and image analysis	Early identification of crop stress, pests and diseases can support faster and more targeted management [41].
Farm labour and operations	Mechanisation, robotics and automation	Reduces physical drudgery, improves the speed of farm operations and can help address labour shortages [14].
Climate resilience	Biotechnology, precision agriculture, digital monitoring and AI	Improved crop traits and better monitoring can help farmers respond to drought, heat, disease and other environmental stresses [42].
Decision-making	IoT, AI, remote sensing and digital agriculture platforms	Field, weather and crop information can be combined to support more timely and informed farm decisions [38].

6.1 Effect on Crop Productivity

Improving crop productivity remains one of the main reasons for adopting agricultural technologies. Precision agriculture can help identify variations in soil and crop conditions and allow farmers to adjust inputs according to field requirements. Technologies such as GPS-guided machinery, remote sensing, sensors and variable-rate systems can therefore support more accurate crop management. A recent systematic review reported that precision agriculture technologies can improve crop productivity while also contributing to more efficient use of agricultural inputs, and the broader changes in global agricultural output growth and total factor productivity over different periods are illustrated in Fig. 3.

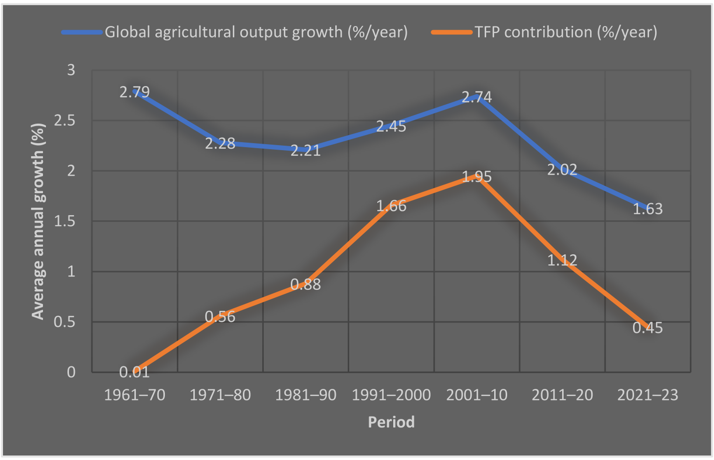

Fig. 3: Global agricultural output growth and TFP (Total Factor Productivity) contribution across different time periods. (Source: USDA, Economic Research Service, International agricultural productivity data product. Data and methods are as of January 2026).

Artificial intelligence is also contributing to productivity-related decision-making, particularly through crop-yield prediction. Machine-learning and deep-learning models can combine information such as temperature, rainfall, soil characteristics, humidity and vegetation indices to estimate expected crop yields. More accurate yield prediction can help farmers and other agricultural stakeholders plan inputs, harvesting, storage and marketing more effectively. Automation can further improve productivity by allowing agricultural operations to be performed more rapidly and at the appropriate stage of crop development. Mechanised and automated systems can reduce delays in activities such as planting, spraying and harvesting, which is particularly important when agricultural operations need to be completed within a limited time. FAO's assessment of agricultural automation indicates that automation can contribute to productivity improvements while also reducing physical drudgery and addressing labour shortages [38].

Advanced technology does not always lead to higher crop yields. The results depend on whether the technology is suitable for the particular farming situation and how effectively it is used. Factors such as crop type, soil conditions, climate, farm size and the farmer's knowledge can all influence the outcome. Therefore, technology should be considered as one component of a broader production system rather than as an independent solution to low agricultural productivity [38].

6.2 Effect on Crop Quality

Science and technology can influence agricultural production through yield and through the quality of harvested products. Biotechnology and genome-editing approaches are being investigated for improving nutritional characteristics, flavour, appearance, shelf life and resistance to stresses that can affect crop quality. Genome editing, for example, has been studied for modifying nutritional components and reducing undesirable characteristics in food crops.

Digital technologies can also contribute to quality management by allowing crops to be monitored throughout the production period. Remote sensing, drones and image-based systems can help identify areas affected by disease or stress before the problem becomes widespread. Since plant diseases can reduce both crop yield and product quality, detecting them early can help farmers take suitable measures before the problem spreads further. Automation can also make some farming operations more consistent. For example, precise application of fertilisers and other inputs, along with automated harvesting systems, can reduce differences that may occur during manual operations. According to FAO, improved product quality is one of the possible benefits of agricultural automation, although the results can vary depending on the technology used and the type of production system [39].

6.5 Effect on Pest and Disease Management

Pests and plant diseases can lead to significant losses in crop production. Traditionally, farmers have relied on field inspection and applied crop-protection measures after visible symptoms appeared. Modern technologies can help identify signs of stress or disease earlier, allowing action to be taken before the problem becomes more widespread. Remote sensing, drones, sensors and machine-learning models are increasingly being used to detect changes in crops that may be linked to disease or stress. Drone-based imaging, for example, can provide detailed information from different parts of a field, while machine-learning methods can help analyse these images and identify possible disease symptoms [40].

Precision farming can also help reduce unnecessary pesticide use by identifying the areas that actually need treatment. A 2023 meta-analysis covering 239 research articles reported that precision technologies have considerable potential to reduce pesticide use and improve weed-management efficiency, although the results varied depending on the crop, pest, technology and farming system. Moving from treating an entire field uniformly to targeting specific areas can therefore help reduce wastage while maintaining crop protection. At the same time, accurate identification of pests and diseases is important. If an automated system incorrectly identifies a problem, it could lead to unnecessary treatment or allow an actual disease or pest infestation to remain untreated [41].

6.6 Effect on Climate Resilience

Climate variability has made resilience an increasingly important aspect of agricultural production. Science and technology can contribute to resilience through several different pathways. Biotechnology can support the development of crops with improved tolerance to drought, salinity, heat and diseases, while digital technologies can help farmers monitor environmental conditions and respond to changes more quickly. Data-based systems can also support prediction and planning. Weather information, soil measurements, remote-sensing data and crop observations can be combined to identify potential risks and support decisions related to irrigation, planting and crop protection. AI-based yield-prediction systems are one example of how environmental and agricultural data can be used to improve planning under changing conditions.

Climate-smart agricultural approaches have been associated with improvements in productivity, income, resource-use efficiency and resilience in many settings. A 2024 comprehensive review reported that climate-smart practices can improve farm productivity and income while strengthening resilience and reducing production risks, although outcomes depend strongly on local conditions [42,43].

Therefore, technology can contribute to climate resilience, but it should not be viewed as a complete response to climate change. Effective adaptation also requires appropriate crop choices, soil management, water conservation, diversification and supportive agricultural policies.

7. Limitations, Risks and Challenges

Science and technology have created several opportunities to improve agricultural production, but the benefits of these advances are not experienced equally across all farming systems. The adoption of a particular technology can be influenced by factors such as the size of the firm, available financial resources, infrastructure, technical knowledge and how well the technology fits local farming practises and conditions. Farmers may also hesitate to adopt advanced technologies because of their high cost, limited infrastructure, lack of technical knowledge and concerns about how reliable and secure the technology is [44].

7.1 Unequal Access Among Farmers

Technological development can also create differences between farmers who have access to advanced equipment and those who do not. Large farms and better-resourced producers may have greater ability to invest in machinery, digital platforms, sensors and professional technical support. Smallholder farmers may have fewer financial resources and less access to credit, infrastructure and extension services. A review of agricultural technologies in smallholder systems found that the impacts of technologies can differ between farmers according to their economic and social circumstances.

This unequal access is important because technological progress does not automatically lead to equal improvements in agricultural livelihoods. If advanced technologies remain concentrated among better-resourced producers, the productivity gap between different groups of farmers may increase. Therefore, technology development needs to be accompanied by appropriate financing, training, extension services and policies that improve access for small-scale producers [44].

7.2 Digital Divide and Infrastructure Limitations

Many modern agricultural technologies depend on reliable electricity, internet connectivity, mobile networks and digital infrastructure. Sensors and IoT devices need reliable communication networks to transmit the information they collect, while cloud platforms and AI-based applications generally require a stable Internet connection and adequate computing resources in rural areas where connectivity and digital infrastructure may be limited or inconsistent; using these technologies regularly can be difficult. As a result, a system may perform well from a technical perspective but still have limited practical value if the infrastructure needed to operate it is not available.

Digital literacy is another important factor. Farmers need to understand how to operate devices, interpret information and respond to recommendations generated by digital systems. A systematic review of digital agricultural services in low- and middle-income countries identified limited connectivity, low digital literacy, inadequate infrastructure and affordability as important barriers to wider adoption.

Therefore, introducing advanced equipment without providing appropriate training and technical support may not result in effective adoption. Technologies designed for agriculture should be sufficiently simple, reliable and appropriate for the conditions in which they are expected to operate [45].

7.3 Lack of Technical Knowledge and Training

Modern agricultural systems increasingly require farmers and agricultural workers to understand digital tools, sensors, data interpretation and automated equipment. Lack of technical knowledge can make farmers hesitant to adopt technologies, particularly when they are unfamiliar with their operation or uncertain about their economic benefits. Recent research on digital agriculture adoption has identified technical knowledge and training as factors influencing farmers' willingness and ability to adopt new technologies [43].

Training should therefore be considered part of the technology itself rather than an additional activity after installation. Farmers also need practical training on how to operate and maintain the equipment, understand the information provided by these systems and decide when a technological recommendation may not be suitable. Improving agricultural extension and support services can help farmers use new technologies more effectively and connect technological developments with their actual needs in the field [44].

7.4 Dependence on Technology and Technical Support

Another concern is the increasing dependence on complex technological systems. When farming operations rely heavily on automated machinery, cloud-based platforms or connected sensors, technical failure can interfere with routine activities. Problems such as damaged sensors, common network interruptions, software errors, or difficulty in obtaining replacement parts may reduce the reliability of these systems and cause delays in farm operations. For this reason, the continued use of agricultural technologies requires not only the initial investment in equipment but also regular maintenance, technical support and access to replacement components. Farmers also need access to maintenance services, spare parts, software support and trained personnel. Technologies that cannot be easily repaired or supported locally may be difficult to maintain in rural areas where technical assistance is limited [45].

Overall, these challenges show that developing a new agricultural technology is only one part of the process. Affordability, infrastructure, farmer training, environmental responsibility, data protection and local suitability are equally important. The future development of agricultural technologies should therefore focus on making systems more advanced and on making them practical and accessible to the farmers who need them.

8. Conclusion

Science and technology have changed agriculture considerably, from the use of simple tools and machinery to the present use of biotechnology, precision farming, IoT, artificial intelligence, drones and agricultural robots. These developments have made it possible to monitor crops more closely, use water and other inputs more efficiently, reduce some labour-intensive activities and make farming decisions using better information. At the same time, the benefits of these technologies are not the same for every farmer. High costs, limited infrastructure, lack of technical knowledge and unequal access can make advanced technologies difficult to adopt, particularly for small-scale farmers.

Therefore, the future of agricultural production should not be based simply on using more advanced technology. The technology also needs to be practical, affordable and suitable for the conditions in which farmers actually work. Combining scientific knowledge with digital tools, automation and the experience of farmers can provide a more useful approach than depending on technology alone. In the coming years, the integration of AIOT, biotechnology, robotics and precision agriculture is likely to create More opportunities for improving Farm productivity and managing agricultural resources more efficiently. However, the usefulness of these developments will depend on more than technological progress itself. Farmers will need appropriate training, reliable infrastructure and technologies that take environmental considerations into account. Continued technical and institutional support will also be important, particularly to help farmers understand, operate and maintain these systems under actual field conditions. This will determine whether emerging technologies can move beyond controlled or large-scale applications and provide practical benefits across different types of farming systems.

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