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Technology for a Food-secure Future: A Review of Technology Advances in Sustainable Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

There is no doubt that advanced technologies play a very important and crucial role in driving the agricultural sustainable practices in order to satisfy the increasing demand for food production as well as to minimize environmental impacts. This review article aims to provide comprehensive points of view regarding a current state as well as the future advances in smart farming techniques for developing an agricultural sustainability. The digital sensors are considered as key techniques for agricultural transformation which provide an accurate managing and monitoring the various agricultural activities such as crop production, soil moisture, micro climate data, and others. Valuable detailed data are acquired by these sensors to be delivered to the farmers in order to make suitable decisions, ensuring the sustainable and efficient utilization of the agricultural resources. Moreover, managing irrigation using the advanced technologies is benefited wireless monitoring remotely and controlling systems. These technologies and advanced tools help the farmers to reduce water consumption and increase their benefits as well as promotes sustainable management practices of the water resources. Additionally, the drones such as unmanned aerial vehicles (UAVs) can be attached with several kinds of sensors or cameras for capturing detailed information of crop health, soil status, required fertilizers, irrigation, and pesticides. Besides these benefits of drones, they provide a function of an early detection of agricultural problems which allow the decision makers for taking suitable actions. Furthermore, the biotechnology advances such as CRISPR gene editing, and transgenic animals' developing are very beneficial for enhancing the crop yield, disease resistance, and nutrients availability, and agricultural sustainability. The precision agriculture (PA) integration with geographic information system (GIS) and remote sensing (RS) provides site-specific management and its decisions in order to optimize the inputs utilization, waste reduce, and sustainable practices promotion. Also, advanced technologies' application (i.e. artificial intelligence 'AI', machine learning 'ML', and the Internet of Things 'IoT') has been found to be a promising for achieving an agricultural sustainability. Therefore, by using these powerful technologies, the farmers can enhance an agricultural production, decrease an environmental effect and achieve the food security.

Keywords: Advanced technologies; biotechnology; sustainable agriculture; precision agriculture; smart farming.

1. INTRODUCTION

Applications of recent technologies in agricultural sustainability are important in order to enhance the agricultural production and minimize the environmental effects. There are different innovative techniques that are integrated to face the challenges of food security, resource conservation, as well as climatic changes. The various kinds of the digital sensors are used for the main objective of agricultural transform by allowing the practices of real-time detection, actionable information that provide sustainability [1]. These sensors are capable to detect, recognize, characterize, estimate and predict different agricultural activities such as crop health, soil status, moisture levels, livestock size, and environment factors, which help the farmers in optimizing benefits and managing their resources as well as reducing the environmental harms. Integrating the digital sensors with the agricultural practices can contribute significant in mitigating the food security, climate change and other risks and helping in achieving the agricultural sustainability [2].

The precision agriculture (PA) has been found to be an optimal model for understanding the potential of the advanced technologies whereas the combining of the data analytics, machine learning (ML), artificial intelligence (AI), remote sensing (RS), geographical information systems (GIS), internet of things (IoT), and other techniques provide a significant aid for enhancing agriculture productivity and sustainability. Moreover, an optimal utilization of these techniques helps the farmers for optimizing the environmental resources, enhancing the crops' yields, and reducing the challenges [3,4].

Drone agriculture is a very recent concept which has been found to help the agricultural sector for achieving the agricultural sustainability gools as well as the PA objectives. The drones provide the farmers with valuable data which help in making decisions and taking good actions for optimizing the agricultural operations and enhancing sustainability. Through acquiring soil, crop, water, urban, and others information, the management of the agricultural activates comes easier [5]. The market of drone agriculture technology continues growing whereas integration of drones and the agricultural practices is mandatory to fill the gap between the population demand and the food production as well as to minimize the environmental impacts.

Moreover, there are some advances in biotechnology sector as described by Tyczewska et al. [6] which reshaping the landscape of agriculture as well as providing the innovative solution for improving the food security, sustainability, and agricultural production [7]. Utilizing these advances such as genetical engineering, a CRISPR-Cas technique, as well as microbial biotechnology, an agricultural sector being capable to face several challenges, and minimizing the environment’s impacts. By focusing on the considerations, regulations, ethics, and public concerns, the benefits of the biotechnology which achieve the sustainable agriculture on the basis of the research and development cover.

Another field of applications regarding the very advanced technologies is the automation and robotics techniques which are providing several benefits to the agricultural sector, allowing innovative advantages to improve the crops’ productivity. An integration of these tools with the precision farming (PF), different agricultural practices can be managed easily such as seeding, irrigation, fertilization, pesticides addition, harvesting, and others. For controlling these agricultural activities, for example the advances irrigation systems are considered as a potential tool for providing effective water consumption for the farmers, enhancing the crop production as well as promote the sustainability. Therefore, integrating these advanced techniques with the RS, AI, ML, and data analytics allow possible chances for mitigating several problems such as water scarcity, climate change, and food security [8].

Another application of the advanced techniques in agriculture is the integrated pest management (IPM) which uses the eco-friendly methodologies for assure the effectivity of controlling the pest and diseases as well as reducing the cost structure of using the chemical pesticides or sterilizers. The IPM when integrated which the IoT, drone agriculture, and AI tools, its efficiency will be doubled in order to enhance the agriculture production and mitigate the climate change [9]. By utilizing the IoT, the agricultural transformation can be significantly fastened. The IoT is very crucial for the agriculture whereas structured of several advanced tools such as the global positioning system (GPS), different sensors (controlling, moving, rotating, etc.), drones, antennas, controlling units and others. These components are capable to provide very detailed information about each centimeter of the agricultural field and helping in real-time monitoring, decision-making, and improving the agricultural resources. The IoT also helps in monitoring the PA and livestock as well as the smart greenhouses. Moreover, it fastening and doubling the efficiency and productivity of the agricultural activities in a sustainable way. The IoT in the agricultural sector increases with a potential of future growing and expanding [10].

The GIS is a very effective tool for agricultural transformation which considered as an effective, potential, powerful and cheap technique for collecting, analysis, and visualizing the different kinds of the data. Moreover, the GIS technique corporates in different agricultural applications such the PA, crop monitoring, water level’s estimating, soil properties interpolation and mapping, and livestock tracking. Additionally, the GIS is capable to enhance the quality of the decision-making process as well as promote the sustainability. An integration of the GIs, AI, and RS is very compulsory for achieving the agricultural sustainability in all agricultural activities [11].

Furthermore, the advanced solutions which obtained by the renewable energy sources are very essential to create sustainable and transformed future of an agriculture. Harnessing the different kinds of the renewable energy sources such as hydropower, solar, wind, geothermal, and biomass energies will help the farmers in reducing the environmental challenges, enhancing the efficiency of the energy, and improving the economic viability of these resources. The smart greenhouses are considered as a significant advance for agricultural technologies which offers innovations and solutions used for enhancing the crop productivity, optimizing the utilized resources as well as promoting the agricultural sustainability. The smart greenhouses combined with the IoT, data analytics, and smart sensors, can be utilized

in adapting the climatic changes and improving the crops yield [12].
One of the most important advancements in the agricultural technology is the vertical farming which considered as a transformative agricultural technique, capable to maximize the consumed spaces, conserve the available resources, and promote the sustainable productivity of the food [13]. By utilizing these techniques, the agriculture will be facing the urbanization, growing population and food security challenges. Moreover, the blockchain technique has been found to be a potential tool for improving the transparency and effectivity through the supply chain of the food.

Therefore, these technologies are found to create more sustainable agricultural sector through improving the agriculture efficiency, decreasing the wastage, and improving the resilience of food systems to face the globe challenges. Furthermore, these technologies are enhancing an agricultural sector, enabling sustainable production of the food as well as mitigating the challenges resulted from the global population growth and climatic changes. Thus, the main objective of this review is to overview the different advanced technologies in an agricultural sector.

1.1 Digital Sensors

The digital sensors are playing a very important role in managing and monitoring different agricultural activities like soil nutrient, moisture, and temperature status as well as providing a real-time information which contribute in helping the farmers for taking a suitable actions and decisions against several activities such as irrigation, fertilization and pest-controlling. These sensors were found to provide solutions for the ultimately leading in better resource management and wastes reduce. There are many types, uses, benefits and applications of the digital sensors in agriculture and are explained below [14].

1.2 Types of Digital Sensors

1.2.1 Soil sensors

There are various kinds of the soil sensors as described by Yin et al. [15] which are utilized for measuring different soil physical and chemical parameters such as pH, soil salinity as expressed by the electrical conductivity (EC), soil moisture content, soil temperature, macronutrients such as (nitrogen ‘N’, phosphorus ‘P’, and potassium ‘K’); and micronutrients such as (iron ‘Fe’, manganese ‘Mn’, copper ‘Cu’, and zinc ‘Zn’). By using these sensors, valuable information can be collected to help the farmers in understanding of the soil quality, health and fertility status, and contributing in the PA practices. These data are very important to achieve better management of the land resources as well as enhance the agricultural productivity. These sensors are such as laboratory-based (i.e. pH meter, atomic absorption spectrometer, spectrophotometer, flame photometer, spectroradiometer, etc.); or field-based sensors (i.e. potentiometer, spectroradiometer, SPAD, etc.); airborne-based sensors (i.e. UAVs, aero planes, etc.); and satellite-based sensors (i.e. hyperspectral, multispectral, thermal, radiometers, etc.).

1.2.2 Crop sensors

These sensors are designed to measure or estimate the crop canopy and determine vegetation morphological parameters such as leaf area index (LAI), pigments (chlorophylls, anthocyanin, etc.). These sensors are utilized also for monitoring the plant health and growth stages. Moreover, these sensors are used for detecting the nutrients deficiency, infectious diseases and pests by using the reflectance, absorbance and fluorescence types of electromagnetic waves. There is aerial or satellite sensors which can be utilized in estimating the crop health by applying the normalized difference vegetation index (NDVI), which provide good indicator for the requirement of the fertilization or pest control [16].

1.2.3 Livestock sensors

Drones for instance, are used for livestock tracking and management [17]. These sensors are used for monitoring an animal health, behaviors, and environment conditions. Moreover, these are utilized for detect and track the vital signs, feeding pattern, and movements in order to help farmers with sufficient information which can optimize the animal welfare and production.

1.2.4 Weather sensors

These sensors are collecting the data related to the atmospheric conditions (temperature, humidity, precipitation, wind, etc.) which are used in estimating and predicting several weather patterns and optimizing the cultivating and harvesting programs. These sensors can help the farmers in minimizing the energy consuming and reducing the possible risks related to changes in the weather conditions [18].

2. APPLICATIONS OF DIGITAL SENSORS IN SUSTAINABLE AGRICULTURE

2.1 Precision Agriculture (PA)

The digital sensors are utilized for the PA activities whereas collecting detailed information and helping the decision-making for taking suitable actions and decisions. An integration of AI, data analytics, sensors and ML algorithms provide the farmers with a comprehensive understanding of their practices and activities in the conditions of the fields. This approach achieves the main goal of the PA which increase the agricultural production by decreasing the inputs' costs [19].

2.2 Remote Sensing and Satellite Technology

The advanced sensors which are used for the agricultural purposes as described by Kumar et al. [20] can be attached with the satellites platforms whereas the RS technique able to support the users or decisionmakers with accurate information. These sensors also can be fixed on the UAVs, or on the ground-based platforms to provide a complete vision about the agricultural activities. Additionally, these techniques provide large scales monitoring related to the crop health, soil conditions, and environmental changes.

2.3 Data-Driven Decision Making

These advanced sensors offer detailed observed data that can be combined with the farm management information systems (FMIS) and enterprise resource planning (ERP) in order to analyze the agricultural activities comprehensively as well as to maximize the uses of the resources and minimizing the agricultural wastes [21].

2.4 Environmental Monitoring

These digital sensors can be used in managing and monitoring the different environmental factors (i.e. greenhouse gas emissions, soil health, etc.). These benefits can help either directly or indirectly in enhancing the total production of the agriculture and reducing the effects of the harmful materials' carbon footprint and improve an ecological balance [22].

2.5 Precision Agriculture (PA)

In the PA, the GPS technology and data analytics are incorporated for a full monitoring of the farming practices. This technique is very crucial for the accurate daily-bases of fertilization, irrigation and pesticides application as well as reducing the wastes and the impacts on an environment. The PA main objective is the given costs must make profit under precise addition of the agricultural activities. Therefore, an exploration of the PA, principles, techniques, advantages and benefits, limitations and challenges, and applications are discussed below.

2.6 Principles of Precision Agriculture

The PA is operating on the point of view that the areas are not same whereas there is a spatial variability of soil types, moisture level, nutrients availability, and crops health. Therefore, understanding this variation can help the farmers to manage the agricultural practices wisely to meet the actual requirements of their fields. There are some key principles of the PA include the site-specific management, whereas the PA monitor and manage every field part against its distinguished characteristics in order to detect the exact needs of this area [23]. This PA approach can be useful in data collection and analysis of the different sources to get the management actions. The PA is also focusing in resource optimization, whereas an accurate application of the irrigation water, fertilization inputs, and pesticides additions. Therefore, these activities of PA are capable to minimize the agricultural inputs' wastage as well as an environment impact [24].

2.7 Technologies Used in Precision Agriculture

The GPS and GIS are mandatory technologies for the PA, whereas GPS is providing the exact locations for the farmers to understand their fields, while the GIS technology is capable to map and analyze the spatial variability distribution of the different agricultural resources (soil, vegetation, water, nutrients, etc.). Moreover, different sensors are utilized in field observations for monitoring the soil moisture levels, temperature status, soil parameters either in discrete or in real-time detection in order to a quantitative decision of the required irrigation and fertilization [25].

The agricultural drones [26] which attached with several kinds of the sensors are capturing the multi-resolution fields imageries to allow farmers assessing the crop vigor, recognize problem sites, and manage the growth stages. The advanced software is utilized in analyzing the collected sensors' data and develop the prediction models which can be used in crop monitoring and forecasting as well as optimizing the cultivation schedules and recommendations. Furthermore, the IoT components enable communicating and collecting the data for real-time management as well as for providing the automated actions-making.

2.8 Benefits of Precision Agriculture

The PA has many advantages such as described in Karunathilake et al. [27] which increasing an efficiency of the agricultural inputs, therefore the farmers being capable to maximize these available resources and minimize cost and waste. The PA has higher crop yields whereas the accurate managements cause the improvement in the crop health and yield. The cost saving is an important advantage for the PA which the agricultural practices can be applied only when are needed and significant profitability can be achieved. Another advantage of the PA is an environmental impact whereas it helps in reducing the chemicals and increasing the eco-friendly materials as well as clean water and atmosphere. The PA contributes in enhancing the decision-making process in situ in order to provide a rapid farm management.

2.9 Challenges of Precision Agriculture

Although the advantages of the PA, there are some challenges in data management [27], integration of technologies, cost of implementation, and technical expertise. Regarding management of the data, the obtained size is controlling the behavior of farmers neither accepted nor rejected. However, the high size of the data is hardly accepted by the farmers or decision-makers. The second limitation is an integration to the other technologies whereas integrating multisource data is complex in managing and processing. Moreover, an initial technological invest as well as the provided training for farmers may be as a barrier for some of them. These operations and processes need additional experiences to deal with many kinds of data, interpret, analyze and decision making.

2.10 Agricultural Drones

These drones are utilized in many applications of the agricultural activities, whereas they used for capturing multispectral or hyperspectral images in order to monitor the crops, soil, water, and livestock. The obtained data can be utilized in decision making regarding the irrigation, fertilization, pest control and other agricultural practices. The agricultural drones' industry significantly increased which enable the farmers to reach the sustainable agricultural practices. The UAVs have different types, sizes and technologies whereas there are drones used for pesticide applications, seedings, capturing images, etc.

2.11 Types and applications of Agricultural Drones

Multispectral imaging drones are such as DJI P4 which capture the spectral data in RGB and vis-NIR region in wide spectral bands. The utilization of these data is for NDVI index calculation which used for crop health monitoring as well as soil conditions. These multispectral sensors are limited in their resolution and accuracy although they are considered as potential tools for the PA. The spraying drones for example, DJI Agras T30 drone which is used for spraying the fertilizers or pesticides either chemical or in chemical addition. The path of the drone flight is automated through a suitable software. The fixed-wing drones are optimal for capturing larger scales rapidly, aerial surveying, mapping, and managing the vegetation cover. Moreover, these drones are capable to fly for longer time than other drone types as described in [28].

The agricultural drones can be used for soil and field analysis as these drones are attached with multispectral sensor or camera to capture images and collect data of the soil status, moisture level, nutrients availability and alkalinity. These data are utilized for optimal cultivating crops and understanding the soil management. Crop monitoring is the second application of these drones whereas covering big sized fields is very difficult using the traditional methods of surveying and sampling. However, drones offer high quality and accurate data can be utilized for decision making and monitoring crop health and yield. The agricultural drones which attached with RGB, with multispectral or thermal sensors can identify the dry and wet spots of the acquired images. This information provides the farmers with the sufficient knowledge for optimizing the irrigation programs and for ensuring the water use efficiency. Agricultural drones are also incorporated in spraying pesticides, herbicides, fertilizers and others, whereas these drones can access to difficult places cannot be visited without drone. Moreover, the drones are contributed in the precision planting and dispersing seeds in their patterns optimally and accurately in order to decrease the seed waste. Furthermore, drones are used for security and surveillance whereas the attached cameras monitor the movements of the livestock, therefore these drones are applied for security and tracking the animals [29].

2.12 Benefits of Agricultural Drones

As explained by Rejeb et al. [30], an increasing an efficiency of the agricultural practices and inputs such as irrigation water, fertilization, and pesticides application. These activities are done accurately and where actually needed for maximizing the utilization of the resources and minimizing the wastage. The second benefit is improving the crop yields through crop health monitoring and detecting the crops' problems as well as optimizing the cultivation conditions. Decreasing the agricultural input costs and improving the agricultural production drives to a dramatic saving of the cost and enhancing profitability. The drones' applications can decrease the chemical runoff and environment impacts and enhancing the water conservation and finally improving the sustainability possibilities. By the real time data acquisition of drones, farmers can make suitable actions and decision in suitable timings.

3. CHALLENGES AND LIMITATIONS

There are some limitations and drawbacks of the agricultural drones such as the high initial investment costs; as well as the compatibility issues through the equipment and software. The restrictions of the regulations of using the agricultural drones in many regions are considered as a big obstacle. These drones and their technology require high expertise people as well as the data interpretation, management and analysis are challenges [31].

3.1 Biotechnology

The biotechnology techniques such as genetic modifying as well as the CRISPR gene editing, provides the crop varieties developing which are more resilient, adapted, tolerant to stresses. These advanced techniques make high yields and profits through reducing the chemical fertilization which incorporating in sustainable agricultural practices. There are key advances in an agricultural biotechnology, applications, advantages and challenges which are described as follow.

3.1 Key Advances in Agricultural Biotechnology

Genetic engineering (GE) takes care of a direct manipulation of the DNA in the organisms in order to develop new traits and to enhance current ones for creating genetically modified organisms (GMOs) which have special properties. There are key techniques for the GE such as transgenic technology which involves the inserting genes from one specie to another in order to develop such as pest resistance or herbicide tolerance traits. For instance, the Bt cotton is genetically engineered for expressing some toxins from *Bacillus thuringiensis*, to make it more resistant to certain pests. The CIS-genic and intragenic approaches are involved in transferring several genes from specie to another. Therefore, such approaches are seen as more acceptable to consumers [32].

The CRISPR-Cas9 is an advanced gene-editing technique which is allowing an accurate modification to the genome of an organism; and also creating some changes in the DNA sequences without including foreign genes, making it a powerful tool for developing crops with enhanced traits such as drought resistance, improved nutritional content, and disease resistance. This technology is gaining traction due to its efficiency and potential for regulatory ease compared to traditional GMOs. Moreover, marker-assisted selection (MAS) utilizes molecular markers to select plants with desirable traits during the breeding process. This technique accelerates the traditional breeding methods by allowing breeders to identify and select plants that carry specific genes associated with traits like disease resistance or high yield. This results in faster development of improved crop varieties. Furthermore, the tissue culture techniques allow for the propagation of plants under sterile conditions, enabling the mass production of disease-free and genetically uniform plants. This method is particularly useful for propagating high-value crops and preserving endangered plant species. Additionally, synthetic biology combines biology and engineering to design and construct new biological parts, devices, and systems. In agriculture, it can be used to create microorganisms that enhance soil health, improve nutrient uptake, or even produce biopesticides. This approach holds promise for developing sustainable agricultural practices. Also, the use of beneficial microbes in agriculture can enhance plant growth, suppress diseases, and improve soil health. Microbial inoculants, such as mycorrhizal fungi and nitrogen-fixing bacteria, can be applied to crops to enhance nutrient availability and promote healthy growth [33].

3.2 Applications of Biotechnology in Agriculture

3.2.1 Crop improvement

The biotechnology tools made the development to the crops whereas enhancing the traits as pest and disease resistance through the genetically engineered resistant crops for different kinds of the pests and diseases. These genetical modifications decrease the required quantities of the chemical pesticides as well as helping in promoting an environmental sustainability. Moreover, the herbicide tolerance function can be added to some crops which sensitive to these herbicides for achieving an effective weed management and not harming the growing crop. Furthermore, the nutritional enhancement in the biofortified crops like Golden Rice with vitamin A. the stress tolerance can also be modified in engineered crops against biotic and abiotic stresses (i.e. drought, salinity, and heat) in order to ensure food security, and mitigate the climatic changes [34].

3.2.2 Sustainable practices

The biotechnology is incorporated into the agricultural sustainability through reducing the reliance on chemical inputs, thereby minimizing environmental pollution. Moreover, enhancing resource use efficiency, such as water and fertilizers, through improved crop varieties. Furthermore, supporting conservation efforts by developing crops that require less land and water [35].

4. BENEFITS OF AGRICULTURAL BIOTECHNOLOGY

These benefits can be achieved through the increased crop yields [36], whereas enhanced traits lead to higher productivity, helping to meet the growing global food demand. Additionally, through the reduced environmental impact that lower pesticide and herbicide use decreases chemical runoff and pollution. Moreover, economic benefits can be added as increased efficiency and reduced input costs improve the profitability of farming operations. More important to cares about the food security issue whereas the biotechnological advancements can help ensure a stable food supply in the face of climate change and population growth.

4.1 Challenges and Concerns

Although there are many benefits of the agricultural biotechnology, it faces several challenges such as the regulatory rules whereas the approval process for GMOs can be lengthy and costly, hindering innovation and adoption. Also, public perception in concerning about the safety of GMOs and their impact on health and the environment can lead to consumer resistance. Moreover, the biodiversity loss through the widespread adoption of a few genetically modified crops may threaten agricultural biodiversity and traditional farming practices. Furthermore, ethical considerations whereas the manipulation of genetic material raises ethical questions regarding the extent of human intervention in nature [33].

4.2 Automation and Robotics

The automation technologies like the robotic harvesting and irrigation tools are considered as some of the tools of agricultural transformation [8]. Through using these tools, better performance in the agricultural activities can be achieved with less human intervention as well as labor. These techniques can help in increasing the crops productivity and minimizing the environmental footprint by optimizing resource use. Moreover, the automation systems and robotics are incorporated in many farming practices with a high efficiency, productivity, and sustainability. However, the automation and robotics in agriculture, including their applications, benefits, challenges, and future prospects is described as follows.

5. OVERVIEW OF AUTOMATION AND ROBOTICS IN AGRICULTURE

5.1 Definition and Scope

An agricultural automation is the utilization of technology to complete the agricultural tasks through minimal labor work. The robotics are considered as the design and application of robots to implement the agricultural activities (i.e. planting, harvesting, and monitoring crops). The integration of the automation and robotics is very crucial to the PA in order to maximize the field-level management through the crop farming [37].

5.2 Key Technologies

There are some advanced tools of the robotics or the automated systems such as the autonomous vehicles whereas these are self-driving tractors and harvesters equipped with GPS and advanced sensors can perform tasks such as plowing, seeding, and harvesting without human operators. These vehicles enhance operational efficiency and reduce labor costs. Other tools are the drones such as the UAVs which are used for crop monitoring, spraying pesticides, and mapping fields [38]. Drones attached with the multispectral cameras can evaluate crop health and recognize problems like pest infestations or nutrients' deficiencies. Moreover, the robotics harvester that are modelled for harvesting fruits and vegetables capable to operate either autonomously or semi-autonomously, and significantly reducing the labor required for these responsibilities. They are fixed with advanced sensors and ML codes for identifying ripe produce and navigate sites [32]. Additionally, the integration of robots or Cobots and human laborers, helping in completing the agricultural activities like cultivating, weeding removal, and packing the products. These Cobots improve productivity and safety through taking over repetitive and physically consuming tasks. Furthermore, the sensor techniques which are integrated into agricultural machines to manage the soil conditions, as well as weather patterns, and plant health. These sensors allow real-time data that informs decision-making and optimizes resource use [39].

6. APPLICATIONS OF AUTOMATION AND ROBOTICS

These automated programs and robots are used in several applications [8] like cultivating and seedling whereas the seeders can automatically plant these seeds at accurate depths and spacing, to ensure the growth conditions. This accuracy minimizes seed wastage and enhance plant yield. Another application, is the crop management that drones and ground-based robotics attached by multispectral or hyperspectral cameras help in monitoring crops, evaluate the soil moisture, and identify the diseases in early stage to allow the time for taking suitable action. Furthermore, an irrigation monitoring is other application of an automatic irrigation program which use the sensors to determine the water when and how much water to apply, optimizing water use and reducing waste. Another application is the pest and weed control which the robots can recognize and target specific weeds or pests for treatment, reducing the need for broad-spectrum herbicides and other harmful materials. This targeted approach minimizes environmental impact and improves sustainability. Also, the robotic harvesters can operate continuously, increasing the speed and efficiency of harvesting operations. They can be computed to recognize ripe produce and handle it delicately, reducing damage. Computation in post-harvest process like sorting and packing, enhances efficiency and reduces labor costs when assuring quality control.

7. BENEFITS OF AUTOMATION AND ROBOTICS IN AGRICULTURE

There are some benefits of these technologies whereas this automation is capable to minimize the time and labor needed for different agricultural tasks, providing farmers to concentrate on higher-value processes. Moreover, by reducing labor fees and maximizing used resources, these techniques can cause significant changes in income for farmers. Moreover, these technologies can enable accurate application of all inputs to the agricultural processs (water, fertilizers, pesticides), reducing wastage and improving crop production. These technologies improve sustainable farming activities by minimizing chemical utilization, conserving water, and minimizing soil compaction. The automation support and assess the labor shortages in agriculture by completing difficult tasks cannot be done by human labor [40].

7.1 Challenges and Limitations

There are some drawbacks of these advanced tools [41] are such as the high costs of these techniques as an investment is needed for doing such advanced machines and tools. The cost can be barrier for small and medium farms. Moreover, these farmers require good training to manage, manipulate as well as effectively monitor these automated systems. Also, the utilization of such tools faces a lot of regulatory rules especially those for safety and liability. Moreover, over-reliance on these tools causes vulnerability in the technology event failures or cyber issues. Finally, an integration between various data sources and the interpretation of this data is very complex and needs advanced analytical skills.

7.2 Future Prospects

The future of these tools is promising as ongoing advancements and increasing investment either in research or development. The AI enhances the capability of the agricultural automatic robots in order to enable those to learn from environment and making decisions and changing conditions. Moreover, the development of small robots (which is capable to work together) for efficient performing of the faced tasks is a good area of research. The IoT facilitates more connectivity among devices which allow the real-time sharing data and improving the process of the decision-making. As environmental concerns grow and greater emphasis on those developed technologies can promote sustainable agricultural practices further in a right way.

7.3 Advanced Irrigation Systems

These systems are mandatory for the modern agriculture especially in mitigating the challenges of water scarcity, climate change, and the need for sustainable farming practices. These systems utilize innovative technologies and methodologies to optimize water use, enhance crop yields, and minimize environmental impacts.

8. TYPES OF ADVANCED IRRIGATION SYSTEMS

8.1 Drip Irrigation

The drip irrigation systems directly deliver the water into plants root zone during a network of tubes and emitters. This system decreases the loss of the water because of the evaporation as well as runoff to make it as a one of efficient available irrigation systems. It consists of mainline, sub-mainlines, emitters, and filters. These emitters under two types of pressure (compensating or non-compensating) based on its design. It is suitable to grow crops, orchards, and greenhouse plants. Therefore, the drip irrigation is essential in aridic regions where critical conserving water [42].

8.2 Sprinkler Irrigation

Sprinkler systems similar to the rainfall (precipitation) in which the water is distributed through pipes network and heads' sprayers. These pipes are fixed or moved and are they are suitable for various crops. This system consists of center pivot, lateral move, and stationary systems [43]. The center pivot system is a common and popular in large fields providing reasonable coverage. Sprinklers are utilized to distribute the needed water quantity for the crop.

8.3 Subsurface Irrigation

The subsurface irrigation is considered a minor common system as it is buried lines or tubes under soil to allow the water delivery to move directly into root zone without any wetting of the surface. This method helps in saving the loss of water during the process of evaporation. Therefore, the weed growth decreases and high value of the crops are added whereas these crops can be grown in arid regions [44].

8.4 Smart Irrigation Systems

The smart irrigation systems utilize techniques for automating and optimizing the irrigation process; whereas these systems include weather controllers as well as soil moisture sensors. These systems have also the capabilities to manage the process remotely [45]. The advanced controlling parts can help in adjusting the schedules of the irrigation process during the real-time data collection and includes weather forecasting as well as soil moisture. These tools are improving the efficiency of water, decreasing the costs of labor and improving the plants health through ensuring suitable watering conditions.

8.5 Rainwater Harvesting Systems

The rainwater harvesting systems are able to obtain and keep the precipitation to be used in crops' irrigation. These tools if integrated with current irrigation systems, it will supply the water in dry times. There are some sources of the watersheds like gutters, storage tanks, and filtration units which are used for ensuring the fresh and clean water availability for crops irrigation. This process of harvesting precipitation water is providing an encourage to water use sustainability as well as decrease the groundwater dependency [45].

8.6 Technologies in Advanced Irrigation Systems

8.6.1 Sensors and IoT

Soil moisture sensors are used for measuring the soil moisture content which provides accurate irrigation programming based on actual crop requirements. Afterwards the weather stations type which allows the real-time data acquisition such as (rainfall, temperature, and humidity) to help in adjusting the irrigation practices accordingly. The IOT integration whereas a connection between different sensors and devices, enabling remote monitoring and control of irrigation systems through smartphones or computers [10].

8.6.2 Automation and control systems

The smart controllers can adjust irrigation schedules automatically based on data from sensors and weather forecasts, optimizing water use [46]. Moreover, the remote monitoring allows farmers to manage irrigation systems from anywhere, ensuring timely adjustments and efficient water distribution.

8.6.3 Data analytics

Th predictive analytics can analyze the historical data to forecast water needs and optimize irrigation schedules, enhancing efficiency and crop yield. Also, the decision support systems provide recommendations based on data analysis, helping farmers make informed irrigation decisions [47].

8.7 Benefits of Advanced Irrigation Systems

These automated systems can increase the water efficiency through the significant reduce of the irrigation water wastage by delivering water directly to the plants and minimizing evaporation and runoff. These technologies can increase the crop production by ensuring that crops receive the right amount of water at the right time, these systems can enhance growth and productivity. The costs will be reduced through reducing the water usage and improved efficiency lead to lower operational costs for farmers. Also, the advanced irrigation practices contribute to sustainable agriculture by conserving water resources and reducing environmental impact. These systems can be tailored to different crops and environmental conditions, making them versatile for various agricultural settings [3].

8.8 Challenges and Limitations

There are some challenges [48] of these techniques are such as costs of developing the irrigation systems and they will require investing expenses. The second limitation is that the farmers need advanced training to be able in using these systems and making decisions. Moreover, the rules and regulations as well as the maintenance of these systems are mandatory for ensuring the efficiency of these systems. Thinking for dealing with the possible risks is crucial to increase profit and reduce the costs [49].

8.9 Future Prospects

These irrigation systems are promising and helping in increasing the need for agricultural sustainability. An AI helps in improving the processes of planning and making the decisions when analyzing big data obtained from the on-field observations. The solar energy can be used effectively in the irrigation systems because such energy can decrease the fossil fuels costs and harm effects. Collaboration between researchers, developers and farmers as well as sharing the field data will lead to better water management and irrigation. The governments' role is essential for enhancing the irrigation technologies and this can be achieved through subsidies, grants, and research initiatives aimed at improving water efficiency in agriculture.

9. ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML)

The efficiency of the AI and ML appears when integrated with agriculture to manage, analyze and model big data. These techniques are used for estimating and predicting the performance of the growing crops as well as helping in making decisions. Therefore, this integration will lead to the agricultural sustainability and transformation in industry, operations and productivity.

9.1 Key Applications of AI and ML in Agriculture

9.1.1 Precision farming

AI and ML are considered as a heart of the PA and precision farming. These tools can deal with the agricultural activities at the field and enabling predictive analytics of the multi-sources obtained data (weather, soil, and satellite, crop irrigation). Moreover, providing the moving technology is very effective in application of fertilizers and pesticides in a good way help in reducing wastage and environment impacts. Besides, many automatic vehicles and machines (self-driving tractors or harvesters) which attached with AI to navigate these vehicles is saving costs, energy, and effort [27].

9.1.2 Crop and livestock monitoring

AI and ML codes are used for analyzing the multi-sources data (sensors, drones, and cameras) for managing and monitoring crop health and livestock well-being. The disease and pest detection through identifying early signs of diseases or pest infestations through image recognition, enabling timely interventions. Moreover, the yield prediction by forecasting crop yields based on factors such as weather patterns, soil conditions and plant growth data; as well as the livestock monitoring utilizing the tracking animal behavior, health, and productivity using sensors and computer vision, optimizing management practices [1].

9.1.3 Weed and pest control

AI tools can identify and target specific weeds or pests (Balaska et al., 2023), reducing the need for broad-spectrum herbicides and pesticides. Robotic weeding autonomous robots equipped with computer vision and machine learning algorithms can precisely identify and remove weeds, minimizing manual labor and chemical use. The drones and field sprayers are applied on the pesticide's applications (for instance) only when and where required based on real-time data and maps.

9.1.4 Supply chain optimization

AI and ML are helping in optimizing different aspects of the agriculture supply chains like prediction models of customers demand and consumption for agricultural products using the data of socioeconomic trends. Moreover, optimization of the logistics by enhancing the transportation, delivery tables, and management using AI tools. Furthermore, the quality control utilizing the automating inspection and grading processes using computer vision and machine learning, ensuring consistent product quality [50].

9.2 Challenges and Limitations

AI and ML provide many benefits but they have some challenges associated with availability and quality for the agricultural data. Moreover, integration with agriculture (farmers and settings) with AI and ML technologies is very complicated and costly. Moreover, the common challenges of the all-agricultural technologies are the regulatory, ethical and experience concerns. Furthermore, AI and ML will still continue growing and their applications in agriculture will expand which provide new tools helping in improving agricultural productivity, sustainability, and profitability [51].

9.3 Integrated Pest Management (IPM)

IPM offers different management plans for controlling the diseases and the pests using eco-friendly methods. This technique utilizes the biological control, crop rotation, and resistant crop varieties' methods for reducing the utilization of pesticide and enhancing the green ecosystem and crop productivity.

10. PRINCIPLES OF INTEGRATED PEST MANAGEMENT

The important step in the IPM approach is preventing the pest problems before occurring through some practices (crop rotation, pest-resistant crops, and maintaining healthy soil) and regular managing and controlling the pest populations and recognizing the priority of the pest's harm. This can be done by using some techniques (traps, visual inspections, and scouting) for evaluating the levels of the pests and know if they exceed economic thresholds. The IPM technology establishes action thresholds, which are the pest population levels at which control measures should be implemented [52].

10.1 Advances in Integrated Pest Management

Integrating the IPM technology to the agriculture is very important for achieving better crop production, saving costs and reducing the environmental resources and impacts as well as mitigating the climate changes and enhancing the sustainability. The RS and drones attached with multispectral cameras or sensors are used to manage and monitor the crop yield and for detecting pest effects using images; as well as providing early detection of any issues. An IoT can deal with the soil moisture and weather data in situ for helping the farmers in monitoring their crops and activities; as well as making suitable actions and decisions [53]. Moreover, data analytics, ML, and filed observations (ground truth) are used for helping farmers in analyzing the historical pest data as well as environment conditions and crop health in order to predict the optimize control measures. This predictive capability improves the effectivity of IPM plans. Additionally, biological control recent advancements such as biopesticides development, and deriving products from natural organisms) are very effective on controlling the pests. These tools minimize the risk on beneficial insects as well as eco-friendly. Genetic engineering is another application in order to produce genetically modified plants which are more resistant such as Bt cotton. These GM crops help in minimizing the cost, and chemicals. Furthermore, the IPM it is very important to make software, platforms or specific programs to the farmers helping them in tracking the pest populations, and monitoring the conditions as well as making decisions. These systems provide recommendations based on real-time data, improving the efficiency of pest management practices [54].

10.2 Benefits of Integrated Pest Management

As described by Talaviya et al. [55], IPM provide an eco-friendly product which help in reducing the utilization of the chemicals and preventing the beneficial organisms in a good and sustainable ways. By reducing the chemical pesticides, the farmers will decrease their costs and improve their profitability. Moreover, healthy ecosystems supported by IPM practices lead to improved crop resilience and higher yields. Through utilizing a combination of control methods, IPM helps protect pests from enhancing their resistance to pesticides, ensuring long-term effectivity.

10.3 Challenges and Limitations

The IPM faces several challenges such as knowledge and training whereas the successful implementation of IPM requires knowledge and training for farmers, which may not be readily available in all regions. Moreover, the initial costs through the transition to IPM practices may involve initial costs for training, technology, and monitoring systems [56]. Furthermore, an integration of multiple strategies can be complex, requiring careful planning and management.

10.4 Internet of Things (IoT)

IoT technology integrates sensors and devices connected to the internet, allowing for real-time monitoring and management of agricultural processes. This includes soil moisture sensors, weather stations, and crop health monitors. By collecting and analyzing data, farmers can optimize irrigation, fertilization, and pest control, leading to more sustainable practices and resource conservation. The IoT is revolutionizing agriculture by enabling the collection and exchange of data in real-time, leading to improved decision-making and enhanced productivity. IoT applications in agriculture facilitate smart farming practices, optimizing resource use, increasing yields, and promoting sustainability [57]. A detailed exploration of IoT applications in agriculture, including their technologies, benefits, challenges, and future prospects. Additionally, the IoT refers to a network of interconnected devices embedded with sensors, software, and other technologies that allow them to collect and exchange data over the internet. In agriculture, IoT applications encompass a wide range of technologies that monitor and manage agricultural operations, from crop production to livestock management.

10.5 IoT Applications in Agriculture

10.5.1 Precision agriculture (PA)

The PA utilizes the IoT sensors for monitoring different environmental factors affecting crop growth such as soil moisture sensors, weather stations, and crop health monitoring sensors as previously discussed.

10.5.2 Smart irrigation systems

IoT technology enhances irrigation practices by automating and optimizing water use as the IoT sensors monitor soil moisture levels and weather conditions, automatically adjusting irrigation schedules to ensure crops receive the right amount of water [58]. The drip irrigation systems deliver water directly to the root zone of plants, minimizing evaporation and runoff. IoT sensors can monitor flow rates and detect leaks, ensuring efficient water use.

10.5.3 Livestock monitoring

Zhang et al. [59] pointed out that, the IoT applications extend to livestock management, improving animal health and productivity through wearable sensors which are attached to livestock can monitor health indicators such as heart rate, temperature, and activity levels. This data helps farmers detect illnesses early and manage breeding cycles. Another application of IoT in livestock monitoring is the location tracking using GPS-enabled collars which allow farmers to track the location of their livestock, ensuring they remain within designated areas and preventing loss.

10.5.4 Crop management and monitoring

IoT devices facilitate real-time monitoring of crop conditions by the RS tools whereas the IoT sensors can monitor environmental conditions such as light, temperature, and humidity in greenhouses, optimizing the growing environment for plants. Moreover, the IoT systems can identify pest infestations and plant diseases through image recognition and data analysis, allowing for timely interventions [60].

10.5.5 Supply chain management

IoT technology improves the agricultural supply chain by providing real-time data on product conditions including cold chain monitoring whereas IoT sensors monitor temperature and humidity levels during storage and transportation of perishable goods, ensuring product quality and reducing spoilage [33]. Moreover, the IoT devices can track inventory levels in real-time, helping farmers manage supplies and reduce waste.

10.5.6 Smart greenhouses

IoT applications in smart greenhouses enhance control over growing conditions through utilizing the automated climate control system whereas IoT sensors monitor temperature, humidity, and light levels, automatically adjusting ventilation, heating, and cooling systems to maintain optimal conditions for plant growth. The resource optimization as in smart greenhouses can optimize water and nutrient delivery based on real-time data, improving resource efficiency and crop yields [61].

11. BENEFITS OF IOT IN AGRICULTURE

There are many benefits of the IoT in agricultural activities and practices such as increasing efficiency whereas IoT applications streamline agricultural processes, reducing labor costs and resource waste. Moreover, the Real-time data allows farmers to make informed decisions regarding planting, irrigation, and pest management. Additionally, by optimizing resource use and monitoring crop health, IoT technology can lead to higher yields and better-quality produce [10]. The IoT applications promote sustainable farming practices by conserving water, reducing chemical inputs, and minimizing environmental impact for achieving the sustainability. Besides these benefits, IoT minimize the cost through the efficient resource management and reduced waste which lead to significant cost savings for farmers.

11.1 Geographic Information Systems (GIS)

The GIS technology enables farmers to analyze spatial data related to their fields. It helps in mapping soil types, crop yields, and environmental conditions, allowing for better planning and management of agricultural practices. This data-driven approach supports precision farming, helping to maximize productivity while minimizing inputs and environmental impact.

11.2 Key Applications of GIS in Agriculture

GIS contributes in several agricultural practices such as in Livestock Management, Supply Chain Optimization, Precision Agriculture, irrigation scheduling, soil mapping, crop health management and other applications as describes below.

11.3 Precision Agriculture (PA)

The GIS technique is playing a very vital role in the PA and concentrates on achieving better management of the agricultural activities and crop farming. The GIS is contributing in several applications such as mapping of the different field parameters and objects (soil, crop, water sources, etc.). Therefore, these obtained data and maps are utilized in helping the farmers in improving the planning and crop rotations as well as other practices. The GIS have many tools such as variable rate technology (VRT) which is applied to analyze the spatial data. The farmers can apply fertilizers, pesticides, and water at variable rates across a field based on these collected data. This targeted approach minimizes waste and maximizes crop yield [62]. Additionally, the GIS tools can analyze historical yield data and environmental factors to forecast future crop production. This information helps farmers make informed decisions about planting and resource allocation.

11.4 Crop Health Monitoring

The GIS is contributing in monitoring the crop strength by using different tools like RS and satellite imageries as well as the UAVs' (attach the multispectral cameras). These data help the farmers in evaluating crop health, detecting pests and diseases, as well as monitoring the different stages. Several spectral indices such as NDVI are utilized popularly in assessing the vegetation health. The GIS also utilized in the thermal imaging in order to detect the temperature levels of he scanned plants [63].

11.5 Soil Analysis

The GIS tools are incorporated in the soil health assessment and management like soil mapping whereas GIS can create detailed soil maps that provide information on soil composition, pH levels, and nutrient content [64] as well as LULC analysis [65]. This data is critical for determining appropriate fertilization strategies and improving soil health. Besides soil mapping [66], GIS tools can analyze topographic data to identify areas at risk of soil erosion [67]. This information helps farmers implement conservation practices to protect their soil resources. The GIS is also used in soil characterization, classification, quality and suitability assessment as carried out by Moursy et al. [68,69].

11.6 Water Resource Management

An effective water management is very mandatory for achieving the sustainable agriculture. For example, irrigation planning using the GIS can help the farmers to design an efficient irrigation system through estimating soil moisture, rainfall, and crop water requirements [70]. By achieving this step, the water use will be decreased as well as the wastage. The GIS tools are found to be effective for assessing and predicting flood risks whereas the GIS is using the topography data as well as the historical databases to provide the farmers with these outputs and maps to take suitable action or decision regarding their agricultural activities.

12. RENEWABLE ENERGY SOLUTIONS

Integrating the renewable energy sources (solar and wind power) with agricultural operations reduces reliance on fossil fuels [71]. These technologies can power irrigation systems, greenhouses, and other farm operations, contributing to a lower carbon footprint and promoting ecological balance.

12.1 Key Renewable Energy Solutions in Agriculture

12.1.1 Solar energy

Solar energy is one of the most widely adopted renewable energy sources in agriculture. It involves the use of photovoltaic (PV) panels to convert sunlight into electricity. There are some applications of the solar energy such as electricity generation whereas the solar panels can be installed on rooftops of barns and greenhouses or in open fields to generate electricity for farm operations, including irrigation systems, lighting, and heating. Moreover, solar water heating through solar thermal systems can provide hot water for livestock operations, cleaning, and crop drying. Additionally, heating the greenhouses using solar energy can be used to maintain optimal temperatures in greenhouses, promoting year-round crop production [72].

These solar benefits are such as cost savings as the solar energy can significantly reduce electricity bills and provide long-term savings. It reduces reliance on fossil fuels and lowers carbon footprints. Moreover, farmers can generate their own electricity, reducing vulnerability to energy price fluctuations [71]. There are some challenges are faced by the solar energy such as the upfront investment for solar panel installation can be high, although costs have been decreasing. Also, large solar installations require significant land, which may compete with agricultural production.

12.1.2 Wind energy

Wind energy harnesses the kinetic energy of wind through turbines to generate electricity; and generate the electricity as well as pumping water whereas windmills have traditionally been used for pumping water for irrigation and livestock. This energy source is a consistent source where in areas with strong winds, wind energy can provide a reliable and continuous source of electricity. It has a dual land use whereas wind turbines occupy only a small footprint, allowing for continued agricultural activities around them [73]. There are some challenges of the wind energy such as the intermittency whereas wind energy is variable and depends on weather conditions. The second challenge is the regulatory hurdles in obtaining permits and navigating regulations can be complex.

12.1.3 Biomass energy

Biomass energy is produced from organic materials, including crop residues, animal manure, and dedicated energy crops. It contributes in bioenergy production which it can be converted into biofuels (like biodiesel and ethanol) or used for direct combustion to generate heat and power. The process of anaerobic digestion converts organic waste into biogas, which can be used for heating, electricity generation, or as a vehicle fuel. There are some benefits such as waste reduction through utilizing agricultural waste for energy reduces disposal costs and environmental impact. Also, the local energy production as biomass energy can often be produced on-site, enhancing energy security. The challenges of this source are such as feedstock availability whereas the consistency and availability of biomass feedstock can be unpredictable. The emissions are another challenge although, biomass is renewable, its combustion can produce emissions if not managed properly [74].

12.1.4 Hydropower

Hydropower utilizes flowing water to generate electricity where the farms located near rivers or streams can install small hydropower systems to generate electricity. It helps in irrigation as the hydropower can also be used to pump water for irrigation systems. This source is renewable and low operating costs. It has an environmental impact whereas construction of hydropower systems can disrupt local ecosystems and water flow [71]. Also, the regulatory issues are considered as challenges whereas permitting and environmental assessments can be time-consuming.

12.1.5 Geothermal energy

Geothermal energy utilizes the stable temperatures below the Earth's surface for heating and cooling. This energy is used in warming the greenhouses through geothermal heat pumps which provide consistent heating for greenhouses, reducing energy costs. Additionally, it is used in managing livestock facilities. This kind of energy is efficient whereas geothermal systems are highly efficient and can significantly reduce heating and cooling costs. Also, it provides a renewable source of energy with minimal environmental impact. Unfortunately, this kind of energy has several challenges such as the high initial costs during the installation of geothermal systems can be expensive [75]. Moreover, it is used in site-specific studies whereas its feasibility depends on local geological conditions.

There are some benefits of renewable energy solutions in agriculture including the environmental impact, whereas the renewable energy solutions significantly reduce greenhouse gas emissions and air pollutants compared to fossil fuels. Moreover, economic opportunities which the renewable energy can provide additional income streams for farmers through energy sales and reduced operational costs. Furthermore, by generating their own energy, farmers can reduce their vulnerability to fluctuating energy prices and supply disruptions. Besides, integrating renewable energy supports sustainable farming practices, promoting long-term ecological balance.

13. ADVANCED CROP BREEDING TECHNIQUES

As previously mentioned, the modern breeding techniques, including marker-assisted selection and genome editing (e.g., CRISPR), enable the development of crop varieties that are more resilient to climate change, pests, and diseases. These advancements not only improve yield but also enhance nutritional content and reduce the need for chemical inputs.

13.1 Advanced Crop Breeding Techniques

13.1.1 Marker-Assisted Selection (MAS)

Marker-assisted selection utilizes molecular markers linked to desirable traits to assist in selecting plants with those traits, without needing to phenotype the traits directly. This allows for more breeding cycles in a year and pyramiding of multiple resistance genes. As described by Song et al. [76], there are many advantages of the MAS include: (i) the selection at the seedling stage, reducing time and resources; (ii) ability to select for recessive alleles; and (iii) pyramiding of multiple genes for complex traits.

13.1.2 Doubled Haploid (DH) Technology

Doubled haploid technology involves the production of homozygous lines from heterozygous plants in a single generation. This is achieved by inducing chromosome doubling in haploid cells, either naturally or through chemical treatment. It has benefits of as a rapid development of homozygous lines; ability to fix desirable alleles in a single generation; and it is useful for hybrid breeding and genetic studies [77].

13.1.3 Genomic selection

Selecting genomic and uses in wide genome markers to estimate the breeding value of individuals and allow selecting without phenotyping. It incorporates the developing prediction models using calibration or training dataset and then applying the model to quantitatively estimate the accuracy of untested individuals. It has some advantages such as an ability to select for complex traits with low heritability; reduced phenotyping costs; and accelerated genetic gain per unit of time [78].

13.1.4 Benefits of these advances

The biotechnology as well as the advanced breeding tools when integrated with the conventional breeding methods, can be very beneficial to agriculture. Breeders can develop improved crop varieties more efficiently and with greater precision, addressing the challenges of food security and sustainability in the face of a growing global population and changing climate. All of these achievements can be done only by leveraging modern biotechnology and genomics.

13.2 Smart Greenhouses

Smart greenhouses utilize automatic systems for controlling environment conditions like temperature, humidity, and light. Smart greenhouses can significantly increase crop yields while using resources more efficiently through optimizing these factors. Several sensors and AI tools are helping in managing and monitoring crop health in real-time.

13.3 Key Components of Smart Greenhouses

As explained by Kavga et al. [79], there are five main components of the smart greenhouses (IoT Sensors; automated climate control systems; smart irrigation systems; data analytics and AI; and remote monitoring and control). The IoT sensors are critical for monitoring various parameters within the greenhouse. These sensors can measure temperature, humidity, soil moisture, light intensity, and carbon dioxide levels. The data collected is transmitted in real-time to a central management system for analysis. The automated climate control systems adjust environmental conditions automatically based on sensor data. For example, heating, cooling, and ventilation systems can be controlled to maintain optimal temperatures, while shading systems can adjust light levels. The smart irrigation systems use data from soil moisture sensors to determine when and how much water to apply.

13.4 Benefits of Smart Greenhouses

By maintaining optimal growing conditions, smart greenhouses can significantly enhance crop productivity and quality. Consistent monitoring and adjustments lead to healthier plants and higher yields. Smart greenhouses optimize the use of water, fertilizers, and energy. Automated irrigation and climate control systems reduce waste and lower operational costs. Automation of various processes, such as irrigation and climate control, decreases the need for manual labor, allowing farmers to focus on higher-value tasks. Smart greenhouses contribute to sustainable agriculture by minimizing resource use and reducing the environmental impact of farming practices. Efficient water uses and reduced chemical inputs promote ecological balance. Smart greenhouses can mitigate the effects of climate change by providing controlled environments that are less susceptible to external weather fluctuations. This adaptability ensures consistent production even in adverse conditions [80].

13.5 Vertical Farming

Vertical farming involves growing crops in stacked layers or vertically inclined surfaces, often within controlled environments. This method reduces land use and allows for year-round production while minimizing water and pesticide use. Advanced hydroponic and aeroponic systems are often employed to enhance growth efficiency.

14. KEY METHODS OF VERTICAL FARMING

Hydroponics is first method of the vertical farming which it involves growing plants in nutrient-rich water solutions without soil. Hydroponic systems can be fully automated and allow for precise control over nutrient delivery, promoting faster growth rates. Another method is using the aeroponics in which the plants are suspended in air and misted with nutrient solutions. This method uses less water than hydroponics and promotes rapid growth due to increased oxygen exposure to the roots. Moreover, the aquaponics also can be applied whereas this integrated system combines aquaculture (raising fish) with hydroponics. The waste produced by fish provides organic nutrients for the plants, while the plants help filter and purify the water for the fish, creating a sustainable ecosystem. The last method is the soil-based vertical farming where crops are grown in stacked soil beds. While less common, this method can still utilize vertical space effectively [81].

14.1 Technologies in Vertical Farming

There are some techniques of the vertical farming include the LED Lighting which is efficient in providing an optimal light spectrum for plant growth. These lights can be adjusted to simulate natural sunlight and promote photosynthesis. Another technique is the advanced climate control systems which are capable to monitor and adjust temperature, humidity, and CO_2 levels to create ideal growing conditions. This technology ensures consistent crop quality and reduces the risk of disease. Additionally, the automation technologies, such as robotics and IoT sensors, are increasingly used in vertical farms to monitor plant health, manage nutrient delivery, and optimize resource use. The vertical farms leverage data analytics to monitor growth patterns, predict yields, and optimize growing conditions. This data-driven approach enhances decision-making and improves efficiency [13].

14.2 Benefits of Vertical Farming

There are many benefits of the vertical farming as described by Oh and Lu [82], which it maximizes land use by growing crops in stacked layers, allowing for higher yields in urban areas where space is limited. By locating farms closer to urban centers, vertical farming reduces the distance food must travel, resulting in lower transportation costs and fresher produce for consumers. Moreover, vertical farming methods, particularly hydroponics and aeroponics, use significantly less water than traditional farming, making them more sustainable in water-scarce regions. Also, the controlled environments reduce the need for chemical pesticides, resulting in cleaner and healthier produce. Furthermore, the vertical farms can operate year-round, regardless of external weather conditions, ensuring a consistent supply of fresh produce. Besides these benefits, vertical farming reduces the carbon footprint by minimizing transportation distances and utilizing energy-efficient technologies, vertical farming can significantly reduce the carbon footprint associated with food production.

14.3 Blockchain Technology

Blockchain technology has a potential to enhance traceability and transparency of the food supply chain. Blockchain is helping in ensuring the sustainable sourcing and improving consumer trustability on the food products through providing a secure and immutable record of agricultural practices [83]. Moreover, it is effective to an agricultural sector where it its enhancing transparency, efficiency, and traceability throughout the food supply chain. The decentralized nature of blockchain enhances trust among participants in the agricultural supply chain [84].

15. CONCLUSION

The applications of the advanced technologies in agricultural sustainability are done for improving the agricultural productivity as well as reducing the environmental impacts. Integrating the advanced tools (digital sensors, precision agriculture ‘PA’, drones, and biotechnology) has been found to be effective and potential for solving the problems of the food productivity, resource conserving, and climatic changes. Providing real-time data (in field) and sharing with farmers, researchers, stake-holders, it will be easier for making decision and actions against the agricultural problems. Moreover, these tools enhance the capability of the farmers to improve operations, minimize resource use, and enhance sustainability.

As the PA goals (enhancing the crop productivity and saving the cost structure), this technology will continue as it provides solutions for better management for obtaining optimal profit of the crops as well as minimize the costs. Furthermore, utilization of drones (UAVs) is crucial to estimate the crop, water, and soil properties and further used of these data in building prediction models which are developed by implementing the AI and ML algorithms. Additionally, biotechnology advancements as well as automation are very important for improving the agricultural practices which offer many solutions in order to enhance the agricultural productivity.

Some technologies such as internet of things (IoT), geographic information systems (GIS), remote sensing (RS), and renewable energy are considered as good alternatives for the conventional methods or protocols. Additionally, the smart greenhouses and vertical farming are very necessary for achieving the objectives of resource use maximizing as well as food security ensuring. The blockchain technology can enhance the transparency and traceability in the food supply chain, fostering a more equitable agricultural system.

Therefore, these advanced technologies are not only overviewing how the food is produced but also distinguishing the role of the agricultural practices in fulfilling the growing population demands.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Martos V, Ahmad A, Cartujo P, Ordoñez J. Ensuring agricultural sustainability through remote sensing in the era of agriculture 5.0. Applied Sciences. 2021;11(13):5911.
2. Kayad A, Paraforos DS, Marinello F, Fountas S. Latest advances in sensor applications in agriculture. Agriculture. 2020;10(8):362.
3. Bhat SA, Huang NF. Big data and AI revolution in precision agriculture: Survey and challenges. Ieee Access. 2021;9: 110209-110222.
4. Bezerra BG, Silva CMS, Mendes KR, Mutti PR, Fernandes LS, Marques TV, Silva CLC, Campos S, De Lima Vieira MM, Urbano SA, Difante GDS. CO_2 exchanges and evapotranspiration of a grazed pasture under tropical climate conditions. Agricultural and Forest Meteorology. 2022;323:109088.
5. Tsolakis N, Bechtsis D, Vasileiadis G, Menexes I, Bochtis DD. Sustainability in the digital farming era: A cyber-physical analysis approach for drone applications in agriculture 4.0. In Information and Communication Technologies for Agriculture—Theme IV: Actions. Cham: Springer International Publishing. 2022;29-53.
6. Tyczewsk A, Twardowski T, Woźniak-Gientka E. Agricultural biotechnology for sustainable food security. Trends in Biotechnology. 2023;41(3):331-341.
7. Zhang J, Drury M. Sustainable agriculture in the EU and China: A comparative critical policy analysis approach. Environmental Science and Policy. 2024;157:103789.
8. Mahmud MSA, Abidin MSZ, Emmanuel AA, Hasan HS. Robotics and automation in agriculture: Present and future applications. Applications of Modelling and Simulation. 2020;4:130-140.
9. Angon PB, Mondal S, Jahan I, Datto M, Antu UB, Ayshi FJ, Islam MS. Integrated pest management (IPM) in agriculture and its role in maintaining ecological balance and biodiversity. Advances in Agriculture. 2023;2023(1):5546373.
10. Morchid A, El Alami R, Raezah AA, Sabbar Y. Applications of internet of things (IoT) and sensors technology to increase food security and agricultural Sustainability: Benefits and challenges. Ain Shams Engineering Journal. 2023;102509.
11. Mathenge M, Sonneveld BG, Broerse JE. Application of GIS in agriculture in promoting evidence-informed decision making for improving agriculture sustainability: A systematic review. Sustainability. 2022;14(16):9974.
12. Pata UK. Linking renewable energy, globalization, agriculture, CO2 emissions and ecological footprint in BRIC countries: A sustainability perspective. Renewable Energy. 2021;173:197-208.
13. Mir MS, Naikoo NB, Kanth RH, Bahar FA, Bhat MA, Nazir A, Ahngar TA. Vertical farming: The future of agriculture: A review. The Pharma Innovation Journal. 2022; 11(2):1175-1195.
14. Dayıoğlu MA, Turker U. Digital transformation for sustainable future-

agriculture 4.0: A review. Journal of Agricultural Sciences. 2021;27(4):373-399.
15. Yin H, Cao Y, Marelli B, Zeng X, Mason AJ, Cao C. Soil sensors and plant wearables for smart and precision agriculture. Advanced Materials. 2021;33(20): 2007764.
16. Khan N, Ray RL, Sargani GR, Ihtisham M, Khayyam M, Ismail S. Current progress and future prospects of agriculture technology: Gateway to sustainable agriculture. Sustainability. 2021;13(9): 4883.
17. Neethirajan S, Kemp B. Digital livestock farming. Sensing and Bio-Sensing Research. 2021;32:100408.
18. Ukhurebor KE, Adetunji CO, Olugbemi OT, Nwankwo W, Olayinka AS, Umezuruike C, Hefft DI. Precision agriculture: Weather forecasting for future farming. In Ai, edge and iot-based smart agriculture. Academic Press. 2022;101-121.
19. Priya R, Ramesh D. ML based sustainable precision agriculture: A future generation perspective. Sustainable Computing: Informatics and Systems. 2020;28: 100439.
20. Kumar S, Meena RS, Sheoran S, Jangir CK, Jhariya MK, Banerjee A, Raj A. Remote sensing for agriculture and resource management. In Natural Resources Conservation and Advances for Sustainability. Elsevier. 2022;91-135.
21. Raji E, Ijomah TI, Eyieyien OG. Data-Driven decision making in agriculture and business: The role of advanced analytics. Computer Science and IT Research Journal. 2024;5(7):1565-1575.
22. Koul B, Yakoob M, Shah MP. Agricultural waste management strategies for environmental sustainability. Environmental Research. 2022;206: 112285.
23. Jin XB, Yu XH, Wang XY, Bai YT, Su TL, Kong JL. Deep learning predictor for sustainable precision agriculture based on internet of things system. Sustainability. 2020;12(4):1433.
24. Loures L, Chamizo A, Ferreira P, Loures A, Castanho R, Panagopoulos T. Assessing the effectiveness of precision agriculture management systems in mediterranean small farms. Sustainability. 2020; 12(9):3765.
25. Roy T, George KJ. Precision farming: A step towards sustainable, climate-smart agriculture. Global climate change: Resilient and smart agriculture. 2020;199-220.
26. Nath S. A vision of precision agriculture: Balance between agricultural sustainability and environmental stewardship. Agronomy Journal. 2024;116(3):1126-1143.
27. Karunathilake EMBM, Le AT, Heo S, Chung YS, Mansoor S. The path to smart farming: Innovations and opportunities in precision agriculture. Agriculture. 2023; 13(8):1593.
28. Mahadasa R, Surarapu P, Vadiyala VR, Baddam PR. Utilization of agricultural drones in farming by harnessing the power of aerial intelligence. Malaysian Journal of Medical and Biological Research. 2020;7(2):135-144.
29. Dileep MR, Navaneeth AV, Ullagaddi S, Danti A. A study and analysis on various types of agricultural drones and its applications. In 2020 fifth international conference on research in computational intelligence and communication networks (ICRCICN). IEEE. 2020;181-185.
30. Rejeb A, Abdollahi A, Rejeb K, Treiblmaier H. Drones in agriculture: A review and bibliometric analysis. Computers and Electronics in Agriculture. 2022;198:107017.
31. Ayamga M, Tekinerdogan B, Kassahun A. Exploring the challenges posed by regulations for the use of drones in agriculture in the African context. Land. 2021;10(2):164.
32. Sarfraz S, Ali F, Hameed A, Ahmad Z, Riaz K. Sustainable agriculture through technological innovations. In Sustainable agriculture in the era of the OMICs revolution. Cham: Springer International Publishing. 2023;223-239.
33. Yadav AN, Singh J, Singh C, Yadav N. (Eds.). Current trends in microbial biotechnology for sustainable agriculture. Singapore: Springer; 2021.
34. Gao C. Genome engineering for crop improvement and future agriculture. Cell. 2021;184(6):1621-1635.
35. Rastegari AA, Yadav AN, Yadav N. (Eds.). New and future developments in microbial biotechnology and bioengineering: Trends of microbial biotechnology for sustainable agriculture and biomedicine systems: Diversity and functional perspectives. Elsevier; 2020.
36. Aileni M. Environment sustainability and role of biotechnology. Innovations in Environmental Biotechnology. 2022;21-64.

37. Botta A, Cavallone P. Robotics applied to precision agriculture: the sustainable Agri. q rover case study. In Proceedings of I4SDG Workshop 2021: IFToMM for Sustainable Development Goals 1. Springer International Publishing. 2022; 41-50.
38. Adewusi AO, Asuzu OF, Olorunsogo T, Iwuanyanwu C, Adaga E, Daraojimba DO. AI in precision agriculture: A review of technologies for sustainable farming practices. World Journal of Advanced Research and Reviews. 2024;21(1):2276-2285.
39. Sharma ANJALI. AI and robotics for reducing waste in the food supply chain: Systematic literature review, theoretical framework and research agenda; 2020.
40. Sparrow R, Howard M. Robots in agriculture: Prospects, impacts, ethics, and policy. Precision Agriculture. 2021;22:818-833.
41. Oliveira LF, Moreira AP, Silva MF. Advances in agriculture robotics: A state-of-the-art review and challenges ahead. Robotics. 2021;10(2):52.
42. Vaddula Y, Singh K. Progression of drip irrigation and fertigation in cotton across the globe and its future perspectives for sustainable agriculture: An overview. Applied Water Science. 2023;13(9):177.
43. Taguta C, Dirwai TL, Senzanje A, Sikka A, Mabhaudhi T. Sustainable irrigation technologies: A water-energy-food (WEF) nexus perspective towards achieving more crop per drop per joule per hectare. Environmental Research Letters. 2022;17(7):073003.
44. Lamm FR, Colaizzi PD, Sorensen RB, Bordovsky JP, Dougherty M, Balkcom K, Peters RT. A 2020 vision of subsurface drip irrigation in the US. Transactions of the ASABE. 2021;64(4):1319-1343.
45. Jarimi H, Powell R, Riffat S. Review of sustainable methods for atmospheric water harvesting. International Journal of Low-Carbon Technologies. 2020;15(2):253-276.
46. Kim WS, Lee WS, Kim YJ. A review of the applications of the internet of things (IoT) for agricultural automation. Journal of Biosystems Engineering. 2020;45: 385-400.
47. Singh AK, Kumar SANJEEV, Jyoti BHIM. Influence of climate change on agricultural sustainability in India: A state-wise panel data analysis. Asian Journal of Agriculture. 2022;6(1):15-27.
48. Abioye EA, Abidin MSZ, Mahmud MSA, Buyamin S, Ishak MHI, Abd Rahman MKI, Ramli MSA. A review on monitoring and advanced control strategies for precision irrigation. Computers and Electronics in Agriculture. 2020;173:105441.
49. Balaska V, Adamidou Z, Vryzas Z, Gasteratos A. Sustainable crop protection via robotics and artificial intelligence solutions. Machines. 2023;11(8):774.
50. Sharma R, Kamble SS, Gunasekaran A, Kumar V, Kumar A. A systematic literature review on machine learning applications for sustainable agriculture supply chain performance. Computers and Operations Research. 2020;119:104926.
51. Ahmad L, Nabi F. Agriculture 5.0: Artificial intelligence, IoT and machine learning. CRC Press; 2021.
52. Singh A, Dhiman N, Kar AK, Singh D, Purohit MP, Ghosh D, Patnaik S. Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. Journal of Hazardous Materials. 2020;385:121525.
53. Javaid M, Haleem A, Khan IH, Suman R. Understanding the potential applications of Artificial Intelligence in Agriculture Sector. Advanced Agrochem. 2023;2(1):15-30.
54. Fahad S, Saud S, Akhter A, Bajwa AA, Hassan S, Battaglia M, Irshad I. Bio-based integrated pest management in rice: An agro-ecosystems friendly approach for agricultural sustainability. Journal of the Saudi Society of Agricultural Sciences. 2021;20(2):94-102.
55. Talaviya T, Shah D, Patel N, Yagnik H, Shah M. Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides. Artificial Intelligence in Agriculture. 2020;4:58-73.
56. Nishant R, Kennedy M, Corbett J. Artificial intelligence for sustainability: Challenges, opportunities, and a research agenda. International Journal of Information Management. 2020;53:102104.
57. Salam A. Internet of things in agricultural innovation and security. In Internet of Things for Sustainable Community Development: Wireless Communications, Sensing, and Systems. Cham: Springer International Publishing. 2024;71-112.
58. Sangeetha BP, Kumar N, Ambalgi AP, Haleem SLA, Thilagam K, Vijayakumar P. IOT based smart irrigation management

system for environmental sustainability in India. Sustainable Energy Technologies and Assessments. 2022;52:101973.

59. Zhang M, Wang X, Feng H, Huang Q, Xiao X, Zhang X. Wearable Internet of Things enabled precision livestock farming in smart farms: A review of technical solutions for precise perception, biocompatibility, and sustainability monitoring. Journal of Cleaner Production. 2021;312:127712.
60. Dhanaraju M, Chenniappan P, Ramalingam K, Pazhanivelan S, Kaliaperumal R. Smart farming: Internet of Things (IoT)-based sustainable agriculture. Agriculture. 2022;12(10):1745.
61. Rayhana R, Xiao G, Liu Z. Internet of things empowered smart greenhouse farming. IEEE Journal of Radio Frequency Identification. 2020;4(3):195-211.
62. Elsharkawy MM, Sheta AEAS, D'Antonio P, Abdelwahed MS, Scopa A. Tool for the establishment of agro-management zones using GIS techniques for precision farming in Egypt. Sustainability. 2022;14(9):5437.
63. Ghosh P, Kumpatla SP. GIS applications in agriculture. In Geographic Information Systems and Applications in Coastal Studies. Intech Open; 2022.
64. El-Sayed MA, Abd-Elazem AH, Moursy AR, Mohamed ES, Kucher DE, Fadl ME. Integration vis-NIR spectroscopy and artificial intelligence to predict some soil parameters in arid region: A case study of Wadi Elkobaneyya, South Egypt. Agronomy. 2023;13(3):935.
65. Selmy SA, Kucher DE, Mozgeris G, Moursy AR, Jimenez-Ballesta R, Kucher OD, Mustafa ARA. Detecting, analyzing, and predicting land use/land cover (LULC) changes in arid regions using landsat images, CA-Markov hybrid model, and GIS techniques. Remote Sensing. 2023;15(23): 5522.
66. Abd-Elazem AH, El-Sayed MA, Abdelsalam AH, Moursy AR. Soil quality and land capability evaluation for agriculture in Balat area, El Dakhla Oasis, western Desert, Egypt. Journal of the Saudi Society of Agricultural Sciences; 2024a.
67. Abd-Elazem AH, El-Sayed MA, Fadl ME, Zekari M, Selmy SA, Drosos M, Moursy AR. Estimating soil erodible fraction using multivariate regression and proximal sensing data in Arid Lands, South Egypt. Soil Systems. 2024b;8(2):48.
68. Moursy AR, Abd El-Galil A, Ibrahim MS, Abd El-Hady AA, Mhalla B. Characterization and classification of soils of Wadi Qena, Eastern Desert, Egypt. The Indian Journal of Agricultural Sciences. 2020a;90(8):1544-1554.
69. Moursy AR, Abdelgalil AA, Ibrahim MS, Mustafa AA. Land suitability evaluation for different crops in Soils of Eastern Sohag, Egypt. International Journal of Academic and Applied Research (IJAAR). 2020b; 4(7):126-138.
70. Moursy AR, Negim OI. Quality assessment and spatial variability mapping of water sources of Sohag area, Egypt. Alexandria Journal of Soil and Water Sciences. 2022;6(2):63-78.
71. Elahi E, Khalid Z, Zhang Z. Understanding farmers' intention and willingness to install renewable energy technology: A solution to reduce the environmental emissions of agriculture. Applied Energy. 2022;309: 118459.
72. Gorjian S, Calise F, Kant K, Ahamed MS, Copertaro B, Najafi G, Shamshiri RR. A review on opportunities for implementation of solar energy technologies in agricultural greenhouses. Journal of Cleaner Production. 2021;285:124807.
73. Rahman MM, Khan I, Field DL, Techato K, Alameh K. Powering agriculture: Present status, future potential, and challenges of renewable energy applications. Renewable Energy. 2022;188:731-749.
74. Saleem M. Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. Heliyon. 2022;8(2).
75. Tomaszewska B, Akkurt GG, Kaczmarczyk M, Bujakowski W, Keles N, Jarma YA, Kabay N. Utilization of renewable energy sources in desalination of geothermal water for agriculture. Desalination. 2021; 513:115151.
76. Song L, Wang R, Yang X, Zhang A, Liu D. Molecular markers and their applications in marker-assisted selection (MAS) in bread wheat (*Triticum aestivum L.*). Agriculture. 2023;13(3):642.
77. Yali W. Haploids and doubled haploid technology application in modern plant breeding. Journal of Plant Sciences. 2022;10(2):71-75.
78. Bohra A, Chand Jha U, Godwin ID, Kumar Varshney R. Genomic interventions for sustainable agriculture. Plant

Biotechnology Journal. 2020;18(12):2388-2405.
79. Kavga A, Thomopoulos V, Barouchas P, Stefanakis N, Liopa-Tsakalidi A. Research on innovative training on smart greenhouse technologies for economic and environmental sustainability. Sustainability. 2021;13(19):10536.
80. Tripathy PK, Tripathy AK, Agarwal A, Mohanty SP. My Green: An IoT-enabled smart greenhouse for sustainable agriculture. IEEE Consumer Electronics Magazine. 2021;10(4):57-62.
81. Van Gerrewey T, Boon N, Geelen D. Vertical farming: The only way is up? Agronomy. 2021;12(1):2.
82. Oh S, Lu C. Vertical farming-smart urban agriculture for enhancing resilience and sustainability in food security. The Journal of Horticultural Science and Biotechnology. 2023;98(2):133-140.
83. Song L, Luo Y, Chang Z, Jin C, Nicolas M. Blockchain adoption in agricultural supply chain for better sustainability: A game theory perspective. Sustainability. 2022; 14(3):1470.
84. Mukherjee AA, Singh RK, Mishra R, Bag S. Application of blockchain technology for sustainability development in agricultural supply chain: Justification framework. Operations Management Research. 2022;15(1):46-61.

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