The Role of 6G Technology in Smart Farming and Precision Agriculture

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Abstract.

Todays a rapid development of era has transformed conventional agriculture into a modern-day, statistics-pushed industry referred to as clever farming or precision agriculture. one of the key enablers of this alteration is the sixth-era (6G) wireless network era. This studies paper explores the function of 6G in revolutionizing agriculture, that specialize in its implications for smart farming practices. The paper delves into the specific contributions of 6G generation to smart farming, emphasizing excessive-speed connectivity in rural areas, low latency for actual-time facts processing, and significant coverage for IoT devices. actual-international case research and examples illustrate the practical packages of 6G in agriculture. moreover, the paper addresses the pressing demanding situations coping with the agriculture sector, consisting of the want to fulfil the growing global meals call for, resource shortage, weather exchange, and hard work shortages. It explores how clever farming technologies, driven thru 6G, can mitigate the ones worrying situations by way of the usage of optimizing useful resource usage, lowering waste, and enhancing productiveness. IoT's pivotal function in clever farming is analyzed in element, specializing in its sensor-primarily based statistics collection and data-driven choice-making talents. various programs of IoT in agriculture are highlighted to underscore its transformative capacity. The impact of 6G on rural regions is a critical issue of the paper, because it discusses how 6G era bridges the virtual divide in agriculture. Case studies of 6G deployment in rural farming.

Keywords: 6G Technology, Smart Farming, Sustainable Agriculture, Case Studies

1.Introduction

Farming has always been central to human survival, yet even in the 21st century, agriculture remains largely reliant on manual labour. The advent of 6G technology is revolutionizing this sector by enabling the automation of repetitive and labour- intensive tasks, marking the dawn of a new era in smart agriculture. With sustainability becoming increasingly crucial, smart farming is poised to play a significant role in enhancing food crop production while addressing the pressing need for environmentally friendly practices. By combining 6G technology, edge computing, and Artificial Intelligence (AI), smart agriculture can achieve higher-speed connectivity with reduced latency, potentially transforming the sector as we navigate challenges in resources and production. Agriculture, the backbone of India's economy, has witnessed remarkable growth in recent decades. In the Indian context, agriculture and healthcare remain critical sectors. The true influence of 6G will be seen in its ability to digitally revolutionize these areas. The introduction of 6G is set to disrupt the agricultural sector, bringing significant benefits to the masses. Although 60 percent of the workforce is involved in agriculture, the sector contributes only 18 percent to the GDP. Many inefficiencies in the current agricultural system can be addressed through technological advancements.The introduction of 6G is set to revolutionize agriculture by enabling precision farming, enhancing cost efficiency, optimizing the use of resources for crops and livestock, improving smart farm management, and ensuring better value for end-users. For instance, drones can be utilized for remote farm monitoring, as well as for spraying fertilizers, pesticides, and insecticides. The network program on precision agriculture focuses on crop health, soil quality, post-harvest management, fisheries, and livestock. One of its key objectives is the development of variable-rate technologies (VRTs) for site-specific input management. VRT enables farmers to apply fertilizers, water, pesticides, and seeds at varying rates across their fields. With this technology, 6G-powered sensors can monitor soil properties and crop conditions in real-time. A control system then determines the precise amount of inputs needed for optimal resultsThe adoption of this technology offers significant benefits, including increased production, environmental conservation, and cost reduction. Precision agriculture focuses on improving productivity by enhancing accuracy, precision, and efficiency across all levels. This is achieved through automation, remote sensing, data analytics, and the use of disruptive innovations like 6G. Its primary objectives are profitability, environmental protection, and sustainability.With the integration of 6G-enabled IoT devices, data from multiple sources is continuously collected, updated in real-time, and transmitted to the cloud. In the cloud, AI and ML algorithms analyze this data to generate actionable insights for farmers. These data sources may include soil moisture, weather conditions, seed genetics, crop health, plant vitality, historical yields, soil pH levels, and market crop prices. Powered by 6G-enabled IoT devices, smart agriculture ensures higher-quality crop production and greater efficiency in farming practices.

Figure 1. Agriculture

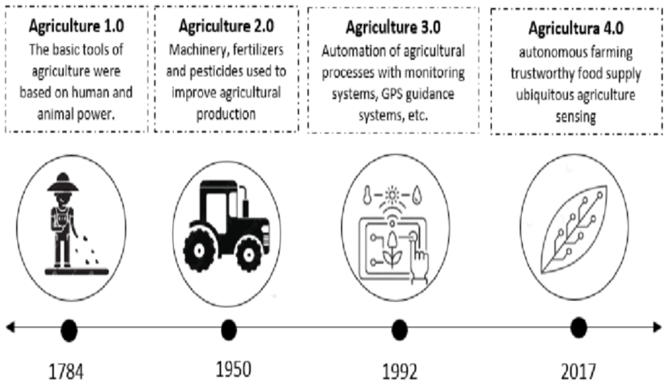

Figure 2. **Chronological change in agricultural revolution**

2. Review of Literature

The global narrative around 6G in agriculture portrays a vibrant vision of its transformative potential. Various pilot projects and initiatives highlight its impact in different areas, including precision farming, livestock monitoring, automated irrigation, and remote agricultural management Tang et al. (2021)[1] The intersection of 5G networks and agriculture offers promising possibilities for transforming smart farming practices in China. This exploration delves into the potential of 5G to revolutionize agriculture through various applications, such as precision farming, livestock monitoring, smart irrigation, drone-based agriculture, and agricultural e-commerce. The discussion also addresses the challenges and opportunities associated with 5G implementation in agriculture, emphasizing key considerations like spectrum allocation, network architecture, security, privacy, energy efficiency, and cost-effectiveness. Hoyos et al. (2022)[2] This study explores the transformative potential of 5G technology in Colombia's agricultural sector, offering a detailed analysis and proposing innovative applications. It categorizes crops by factors such as budget availability, population density, and regional development plans, serving as a valuable guide for creating strategic 5G implementation plans tailored to Colombia's unique agricultural landscape. Li & Li (2020) [3] This paper examines the impact of 5G technology on agricultural efficiency, quality, and sustainability, shedding light on the challenges and opportunities in China’s rural development. It provides actionable recommendations for policymakers and practitioners. The study explores the potential applications of 5G in agriculture, highlighting its key advantages, including high speed, low latency, reliability, and massive connectivity. These characteristics make 5G highly suitable for enabling smart farming, precision agriculture, agricultural IoT, big data, and cloud computing, Hilten & Wolfert (2022)[4] This study explores the intersection of 5G networks and agriculture, focusing on the transformative impact on smart farming practices in China. A key highlight is a 5G-powered robot designed for autonomous weeding and harvesting, showcasing its potential to enhance efficiency and reduce labor dependency. The discussion delves into various 5G-enabled applications, including precision farming, livestock monitoring, smart irrigation, drone-based agriculture, and agricultural e-commerce. Additionally, it examines the challenges and opportunities of implementing 5G in agriculture, offering valuable insights for advancing sustainable and technology-driven farming practices.Tomaszewski & Kołakowski (2023)[5] This paper takes a global perspective, exploring the challenges and opportunities associated with 5G and 6G mobile networks in smart agriculture, forestry, biodiversity monitoring, and water management. It highlights the immense potential of integrating 5G technology to revolutionize these sectors. The study emphasizes how advanced connectivity can drive innovation, improve efficiency, and support sustainable practices in managing natural resources and agricultural ecosystems. Valecce et al. (2019)[6]This study explores the transformative potential of 5G technology in advancing machine-to-machine (M2M) services for agricultural applications, with a particular focus on cellular-connected drones and robots. These cutting-edge technologies play a crucial role in monitoring and managing key aspects of agricultural production, such as soil quality, water usage, pest control, and animal health. By leveraging the high speed, low latency, and reliability of 5G networks, these innovations promise to enhance efficiency, precision, and sustainability in modern farming practices. Waaji et al. (2021)[7] This paper highlights the ground breaking potential of fifth-generation (5G) technology in revolutionizing precision agriculture, with a focus on the Netherlands—a global leader in agricultural innovation. Against the backdrop of a steadily growing global population, the study emphasizes the critical role of advanced technology in meeting rising food demands, positioning 5G as a key enabler of the next wave of agricultural innovation. The Netherlands, with its extensive 4G coverage and anticipated transition to 5G, provides an ideal environment for piloting and implementing transformative applications. The paper introduces cutting-edge use cases, including remote support tools, smart fencing, GPS-enabled cow monitoring, crop inspection drones, and weeding robots. These applications leverage 5G's high bandwidth, low latency, and mobile edge computing capabilities to enhance agricultural efficiency and sustainability. However, the paper also addresses the challenges of global rural connectivity, identifying a potential deadlock between the telecom and agriculture sectors that could hinder widespread adoption. Hsu et al. (2019) [8] This study introduces a pioneering application of fifth-generation (5G) technology in the agricultural sector through the development of an innovative Image Electronic Fence (IEF) system for smart farms in Taiwan. Utilizing 5G's advanced capabilities, the IEF system facilitates real-time monitoring and control of livestock and crops. It integrates a network of cameras, a cloud server, and mobile applications to provide seamless connectivity and management. This breakthrough demonstrates how 5G technology can enhance precision farming by enabling efficient, automated, and data-driven agricultural practices.

3. 6G Technology

The integration of 6G technology in agriculture is revolutionizing farming practices by improving efficiency, boosting production through optimized input use, and monitoring crop and soil health. By analyzing vast amounts of farm and climate data, 6G technology enables farmers to make more informed decisions. This advanced technology is increasingly applied in agricultural mechanization, encompassing areas such as tillage, sowing, crop protection, and harvesting. Modern tools like mechatronics, robotics, and drones are incorporated to enhance these processes further.Robotic digging operations, enabled by IoT and 6G connectivity, are increasingly utilized during the growing and post-harvest seasons. 6G-powered systems provide a wide range of functionalities, including data collection, communication infrastructure for connecting smart devices to user applications via the internet, cloud-based smart data analytics, decision-making support, and operational automation. These advancements bring innovative approaches to agriculture, particularly in tillage operations. Land preparation, a critical and energy-intensive part of farming, has largely been mechanized using tractors and power tillers. However, tractor operators often face challenges like noise, vibrations, dust, and other physical stresses. Additionally, the high cost of labor, labor shortages, and human error have driven the development of self-sufficient agricultural vehicles. Since the late 20th century [9], significant advancements in farm vehicle automation and autonomous driving technologies have emerged, transforming the landscape of modern agriculture [10] Hydrogen-powered 6G-enabled smart self-driving tractors have been developed to enhance land preparation with greater efficiency and field capacity. For example, China has pioneered the creation of such a tractor, integrating cutting-edge technologies to improve agricultural productivity. These innovative machines utilize hydrogen as a clean energy source, combined with 6G connectivity, to enable autonomous operation and advanced precision in farming tasks. [11]. High-speed vehicle-to-vehicle (V2V) connectivity is a transformative feature enabled by advanced technologies like 6G. In agriculture, this connectivity allows autonomous vehicles, such as tractors and harvesters, to communicate seamlessly in real-time. This capability enhances coordination during complex farming operations, such as synchronized plowing, planting, and harvesting. By sharing data such as speed, position, and task progress, V2V connectivity improves efficiency, reduces the likelihood of errors, and optimizes resource use. Additionally, this interconnected network of smart vehicles contributes to safer and more precise agricultural practices, ultimately boosting productivity and sustainability in modern farming [12],The characteristics of 6G technology significantly enhance the autonomous operation of smart farms, particularly in the use of unmanned ground vehicles (UGVs). With its low latency, high speed, and reliable connectivity, 6G allows UGVs to perform complex tasks such as planting, harvesting, and monitoring crops without human intervention. The real-time communication between these vehicles and the central system enables precise control and coordination, optimizing farm operations. Additionally, 6G-enabled autonomous vehicles can be integrated with intelligent delivery systems, allowing for efficient transportation of goods such as harvested crops, equipment, and supplies across the farm. This improves logistics, reduces labour costs, and boosts the overall efficiency of farm management, paving the way for more sustainable and productive agricultural practices [13] .

6G technology enables seamless communication between devices, smart traffic signs, and other machinery, allowing autonomous systems to make decisions in microseconds. This rapid decision-making ensures that vehicles can follow the desired path, take appropriate actions, and avoid collisions, reducing the risk of accidents. In agriculture, selective movement of autonomous vehicles on farms is made possible through an advanced positioning system, enhanced by 6G connectivity, ensuring precise navigation across fields. For better soil conservation, 6G-enabled systems can also monitor and analyze tillage practices, providing real-time data on soil health and enabling farmers to adopt more sustainable and efficient farming techniques. This allows for optimized land use while minimizing soil degradation, contributing to long-term agricultural sustainability [14] With 6G technology, farmers can take advantage of advanced systems to quantify the mobilized extent of soil, which is essential for assessing the effects of tillage on soil health. Real-time data from sensors embedded in autonomous vehicles and machinery can track soil movement and disturbance during tillage operations. This allows for precise monitoring of soil erosion, compaction, and other variables that affect soil quality.By collecting detailed data on the amount of soil being moved or disturbed, farmers can optimize their tillage practices to minimize soil degradation, improve conservation efforts, and boost crop yields. The integration of 6G-powered systems ensures faster and more accurate assessments, enabling farmers to make timely adjustments and implement better farming strategies [15], The use of plant indices to monitor different tillage methods is an effective way to evaluate and compare their impact on crop growth and soil health. Plant indices, such as the Normalized Difference Vegetation Index (NDVI), are used to assess the health and vigor of plants by analyzing the reflectance of light in various wavelengths. With 6G technology, real-time data collection from sensors on autonomous vehicles or drones can capture these plant indices across different tillage practices.

By comparing the plant indices from areas subjected to various tillage methods, farmers can determine which practices promote better crop growth and soil health. This data helps identify which tillage methods are most effective for optimizing plant growth, reducing soil erosion, and improving long-term soil fertility. Additionally, the use of plant indices allows for precise monitoring of plant stress, pest damage, and other factors, enabling farmers to make data-driven decisions for improved crop management [16] The use of UAVs (Unmanned Aerial Vehicles) to acquire 3D images of crops is crucial for monitoring crop health and improving farm management. With the integration of 6G technology, the acquisition and processing of these images can be made more efficient, allowing for real-time data collection and analysis, which enhances precision in monitoring crop conditions.6G-enabled crop protection and management systems include several essential features such as crop production (yields), profitability, losses, climate forecasting, field mapping, soil nutrient monitoring, and overall data collection, processing, and decision-making. These technologies enable farmers to make informed decisions by offering insights into crop performance, environmental conditions, and soil health. It's estimated that 20-40% of food chain losses occur due to pests and diseases, and with 6G technology, more efficient pest and disease monitoring, prevention, and management can significantly reduce these losses, improving food security and farm profitability [17]. Protection from pests, diseases, animals, and weeds is essential for ensuring sustainable and continuous food production.

Managing these threats effectively is key to maintaining crop health and maximizing yields. The use of several robot weeders, powered by advanced technologies such as 6G, is becoming increasingly popular in modern farming. These robotic systems can autonomously detect and eliminate weeds with precision, reducing the need for harmful chemicals and minimizing soil disturbance.In addition to controlling weeds, these robots can also be equipped with sensors to detect pests and diseases early, enabling targeted interventions that protect crops while minimizing the use of pesticides. This approach not only improves crop yields but also contributes to environmentally friendly farming practices. With the integration of 6G technology, these systems can operate in real-time, efficiently monitoring and managing threats, ensuring a more sustainable and productive agricultural system [18] Robotic weeders have been developed and are now commercially available, playing a critical role in modern agriculture. An essential aspect of robotic weeding is the accurate identification of weeds and crops. This process is enabled by advanced crop signaling techniques, which help distinguish between crops and unwanted weeds.

These signaling methods typically rely on sensors and machine learning algorithms that analyze visual or spectral data, allowing robots to differentiate crops from weeds based on characteristics like color, shape, and growth patterns.By leveraging these crop signaling strategies, robotic weeders can selectively target weeds while avoiding damage to crops. This precision reduces the need for chemical herbicides, decreases soil disruption, and helps maintain sustainable farming practices. As technology advances, these systems will continue to improve, offering even more efficient and environmentally friendly solutions for weed management [19], Neural networks, deep learning, and image processing are key technologies that enable advanced crop signaling and robotic weeding systems.Neural networks are a type of machine learning model that can be trained to recognize patterns in data. In the context of agriculture, they help robots and systems analyze vast amounts of visual data to differentiate between crops and weeds. By training these networks on labeled images of different crops and weeds, they can learn to classify new images accurately.

Deep learning is a subset of neural networks that involves more complex layers of processing, allowing for more precise analysis and decision-making. Deep learning models can process images with high accuracy, even in challenging environments or with varying lighting conditions, enabling the robotic weeders to better identify and target weeds. Image processing involves the use of algorithms to enhance and analyze visual data captured by cameras or sensors. In robotic weeding, image processing techniques are used to enhance the images of crops and weeds, making it easier to detect specific characteristics like color, shape, and texture. These techniques are crucial for enabling robots to make real-time decisions about which plants are crops and which are weeds [20] Recent advancements in selective motion for weed control have greatly benefited from the application of 6G technologies, which enable more precise and efficient weed management. With the ultra-low latency, high-speed connectivity, and massive data transfer capabilities of 6G, systems can now identify and differentiate between weeds and crops with much greater accuracy and finer granularity.The application of 6G technologies enhances the method of weed and plant identification by integrating high-resolution imaging, AI-powered algorithms, and real-time data processing. These technologies allow for faster and more detailed analysis of visual and spectral data captured by drones, sensors, or robotic weeders. For example, 6G-powered systems can process complex patterns in plant structure, color, growth stage, and spectral signatures, making the identification of weeds much more precise and allowing for targeted interventions.With this fine-grained accuracy, robots or autonomous vehicles can selectively target and remove weeds while minimizing damage to crops, optimizing the use of herbicides, and reducing environmental impact. This method of identification and action not only improves crop yields but also contributes to more sustainable and efficient farming practices [21]. Sickness identification in crops using thermal cameras and image processing is an innovative approach that is becoming increasingly effective in modern agriculture.

Thermal cameras capture temperature variations in plants, which can indicate stress caused by pests, diseases, or environmental factors. When crops are affected by diseases or pests, their physiological processes, such as transpiration or heat regulation, can be disrupted, leading to temperature changes that are detectable by thermal imaging.Thermal cameras are used to detect these temperature anomalies in real time. For instance, plants affected by fungal infections or bacterial diseases may show signs of dehydration or altered temperature patterns due to disrupted cellular processes. By capturing these subtle temperature changes, thermal cameras can help farmers identify sick plants early, often before visible symptoms appear.Image processing techniques then analyze the thermal images to identify specific patterns or deviations from normal plant temperatures. Machine learning algorithms can be trained to recognize these patterns and categorize them according to the type of disease or stress affecting the plant.When integrated with 6G technology**,** the data from thermal cameras and image processing systems can be transmitted instantly for cloud-based analysis, allowing for real-time monitoring and decision-making. This enables farmers to take immediate action, such as applying targeted treatments, improving irrigation, or removing infected plants, thereby minimizing crop losses and ensuring more efficient farm management[22], Synthetic intelligence, in combination with other technologies like 6G and IoT, holds the potential to significantly enhance productivity, sustainability, and decision-making in agriculture. It can help farmers tackle complex challenges, automate labor-intensive tasks, and improve overall farm management. [23], 6G technology significantly enhances agricultural practices by enabling novel advancements like nanotechnology, variable-rate application, nutrient deficiency mapping, and selective application, all of which can be powered by 6G connectivity. This high-speed, low-latency network fosters the seamless operation of UAVs (Unmanned Aerial Vehicles), satellites, and other connected systems, accelerating precision farming practices.Satellite images are increasingly used to monitor soil quality changes and understand the influence of field topography on crop production. With 6G's high data transfer capabilities, real-time satellite imagery can be processed and analyzed, enabling farmers to monitor production parameters such as seed quality, fertilizer application, water usage, and pest control with greater precision. This facilitates accurate adjustments to improve crop yields and productivity.Field management automation becomes more advanced with 6G, allowing sensors and devices to gather detailed data that can be used for crop monitoring, enhancing decision-making processes. This data can help detect early warning signs of pests or diseases, enabling farmers to take timely action and prevent significant crop losses. Additionally, fast data transmission allows for accurate mapping and extremely short response times, which are critical for effective nutrient management and the application of fertilizers, pesticides, and water.In the case of UAVs, their role in agriculture has expanded, thanks to 6G technology. UAVs are now utilized for a variety of tasks such as spraying, broadcasting fertilizers and seeds, soil mapping, weed control, and even harvesting. These drones are connected and monitored through 6G communication channels, allowing for precise, real-time control and coordination. This connectivity ensures more efficient and productive farm operations, contributing to sustainable agricultural practices and optimized resource use [24].

UAVs (Unmanned Aerial Vehicles) equipped with various types of nozzles are revolutionizing the spraying of insecticides, herbicides, and even nano-urea, making the application process more precise and efficient. With the ability to target specific areas, these drones minimize waste and reduce the environmental impact of chemicals, ensuring better crop health and sustainability. In addition to spraying, drones are increasingly being used for harvesting**,** not only for traditional crops like coconuts but also for specialized tasks such as honey extraction. This demonstrates the versatility of UAVs in agriculture, allowing farmers to automate and streamline operations that would otherwise require significant manual labour.Furthermore, the use of UAVs in place of traditional ground machines and human labour offers several benefits, particularly in terms of reducing soil compaction and eliminating drudgery. Ground vehicles and human-powered methods often contribute to soil compression, which can negatively affect crop growth and productivity. By utilizing UAVs, farmers can avoid these issues, preserving soil structure and enhancing overall farm efficiency. Overall, UAVs, when integrated with advanced technologies like 6G, are transforming agricultural practices by making operations more efficient, sustainable, and less labor-intensive [25] he application of drones in agricultural logistics might initially seem limited, but in specific scenarios, it proves to be incredibly beneficial. With the integration of 6G technology, the potential for UAVs to operate over vast distances and be controlled from anywhere in the world becomes a reality. Multiple UAVs can communicate with each other and perform synchronized, autonomous flights, making it feasible to deploy a fleet of drones within a single farm boundary to carry out time-sensitive operations efficiently.UAVs equipped with real-time sensors, such as photo processing, machine learning capabilities, 4K video streams for monitoring, and telemetry, can gather crucial data to support farming operations. With 6G, the transmission of these data streams becomes seamless, enabling enhanced operational efficiency, real-time monitoring, and better decision-making across large agricultural areas. This high level of connectivity improves the versatility and utility of UAVs, allowing them to perform a broader range of tasks, from spraying to monitoring crop health and soil conditions. Despite their advantages, agricultural UAVs face challenges like limited lifespan, complex control systems, and a lack of precision application control technology.

To address these issues, 6G-enabled UAV intelligence is crucial. Requirements for smart control, precision, higher functionality, and optimization are driving the development of advanced UAV systems for agricultural spraying. The ability to process large amounts of data in real-time, supported by 6G's high bandwidth and low latency**,** makes this possible, ensuring precise control and more efficient operation. One of the most critical aspects of agricultural productivity is timely harvesting**,** which directly impacts crop yield and quality. Mechanical damage during harvesting can reduce the quality of the produce and lead to increased harvest losses. By utilizing 6G-enabled UAVs**,** farmers can ensure that harvesting is done promptly and with minimal mechanical damage, enhancing overall efficiency and reducing losses. The synchronization of multiple UAVs, real-time monitoring, and precise operations can significantly improve harvest outcomes and support sustainable farming practices.In conclusion, the convergence of UAV technology and 6G will elevate the capabilities of agricultural drones, making them an indispensable tool in optimizing farm operations, improving yield, and minimizing resource waste.Harvesting machines can be classified based on the type of crops they are designed to harvest, such as field crops, fruits, vegetables, and flowers. Each category requires specific machinery to optimize the harvesting process. For example, field crops like rice, wheat, maize, sugarcane, and sorghum are typically harvested using various types of reapers and combine harvesters. These machines are often equipped with auxiliary tools such as hay rakes and balers to manage and process the harvested crop efficiently.The integration of autonomous vehicles and yield monitoring systems is revolutionizing harvesting practices. Autonomous harvesters equipped with yield monitoring technology can provide real-time data on crop performance during harvesting. These systems use sensors to track the amount of crop harvested from different areas of the field, providing valuable insights into field variability and optimizing harvesting efficiency.With the help of 6G technology**,** these autonomous harvesters can communicate and synchronize with other machines and systems in real-time. This enhanced connectivity allows for more efficient, precise, and coordinated harvesting operations. The autonomous systems can also adapt to varying field conditions, adjusting their operations based on factors like crop density, moisture levels, and terrain, ultimately increasing productivity and reducing waste. Moreover, autonomous harvesters can improve the sustainability of farming practices by minimizing crop damage, reducing labour requirements, and allowing for more efficient resource use, thus contributing to both increased crop yield and long-term agricultural sustainability [26], In the realm of agricultural harvesting, the use of 6G technology is enhancing the capabilities of machines, particularly in the automation and optimization of processes like maturity detection and selective harvesting. These advancements are particularly beneficial for crops such as fruits, vegetables, flowers, and plantation crops**.**

For field crops, the focus is often on optimizing harvesting efficiency and yield monitoring. However, for crops that require more delicate handling, like fruits and vegetables, maturity-based selective harvesting is crucial. This process involves harvesting crops at the right time for optimal quality, flavour, and nutritional value. With 6G technology, harvesting machines can now integrate machine vision systems for maturity detection. Using cameras, sensors, and image processing algorithms, these systems can assess the ripeness or readiness of individual crops, ensuring that only mature crops are harvested. Autonomous robots**,** which are now a key part of the harvesting process, come equipped with self-navigation systems**,** selecting arms**,** detection sensors**,** and control systems**.** These robots are able to operate independently in fields, using advanced GPS technology and decision support tools powered by 6G. These tools help guide the robots, enabling them to navigate through fields, select crops based on maturity, and even handle them gently to prevent damage. Moreover, 6G technology enables real-time data processing and communication across the entire farming operation. With ultra-fast connectivity and low latency, the robots can instantly access data from GPS, sensor networks, and cloud-based systems to make real-time decisions on when and where to harvest specific crops. This leads to more efficient use of resources and reduces the need for human intervention, lowering labour costs and improving overall productivity.The integration of data management systems powered by 6G ensures that all harvesting processes are well-coordinated, monitored, and optimized. For instance, data from harvesting robots can be fed into central management systems that track crop progress, monitor environmental conditions, and assess the effectiveness of the harvesting process. This information can then be analyzed using AI and machine learning algorithms to improve future harvesting strategies and resource allocation.Overall, the combination of 6G technology, robotic automation, GPS systems, and decision support tools provides a powerful solution for selective harvesting. It enables highly efficient, precise, and sustainable farming practices, especially for crops that require delicate handling and accurate maturity detection. [27].

With 6G technology, the capabilities of agricultural robots, particularly in covered cultivation farms for vegetables and flowers, are significantly enhanced. These robots can now be remotely operated with simultaneous and powerful data transfer, which is essential for the efficient and accurate harvesting of delicate crops. In these settings, robots equipped with a variety of sensors can perform tasks autonomously and in real-time, optimizing the entire harvesting process. One of the key advantages of 6G in this context is the ability to integrate advanced object detection systems using machine vision, which allows robots to identify and distinguish between different objects in the environment. For instance, robots can use sensors to detect produce, plants, and potential obstacles in orchards or greenhouse settings. This is especially important in orchards, where the layout can be complex and the trees and plants need to be navigated around without causing damage. The high bandwidth and low latency of 6G enable real-time communication between the robot and the central control system, ensuring precise and accurate decisions as the robot performs tasks like harvesting, sorting, and transporting crops. For example, when harvesting vegetables or flowers, these robots can rely on object detection to assess the ripeness of the produce, identify the best harvesting route, and avoid obstacles like low-hanging branches or other equipment. The sensors on the robots can also help them assess the condition of the crops, detect diseases or damage, and make adjustments in real time, ensuring that only the healthiest produce is harvested. Moreover, in covered cultivation farms, where controlled environments are essential for maximizing crop yield and quality, 6G-powered robots are ideal. These robots can be connected to a network of sensors monitoring the environment (temperature, humidity, light levels) and can adapt their operations based on this data. The real-time feedback loop enabled by 6G allows for more efficient and accurate harvesting, contributing to higher yields and reduced waste. Ultimately, 6G technology significantly enhances the automation of vegetable and flower harvesting, especially in environments like orchards and greenhouses, where obstacles and complex crop arrangements require highly advanced detection and navigation systems. The ability to remotely control these robots while receiving live data ensures that farming practices become more precise, efficient, and sustainable [28] .

In greenhouses and covered cultivation farms, the application of 6G technology is poised to revolutionize the way robotic harvesters operate by enhancing their ability to sense the maturity of produce, navigate autonomously, and adapt to dynamic field conditions. Several key aspects of robotic harvesting can be significantly improved through 6G, Sensing Maturity With the power of 6G**,** harvesters equipped with advanced sensors and machine vision can accurately detect the maturity of crops by analyzing characteristics like color**,** size**,** and texture. These sensors can be coupled with AI algorithms to make real-time decisions about when to harvest produce, ensuring optimal quality and minimizing waste. Navigation and Autonomous Driving One of the major contributions of 6G technology is in improving the navigation of autonomous harvesters. The self-driving capabilities, combined with direction-following technology, allow robotic harvesters to navigate through the fields or greenhouses autonomously. This includes avoiding obstacles, optimizing travel routes, and ensuring smooth operation even in complex farming environments. GPS and real-time positioning systems powered by 6G enable precise movement and operation, even over large and variable farm areas. Dynamic Adaptation the goal of 6G-enabled harvesters is to increase output by allowing the machines to dynamically adjust their performance based on changing soil conditions**,** plant health**,** moisture levels, and grain conditions. This ensures that harvesting operations are continuously optimized for the conditions of the field, improving both efficiency and crop quality. Harvesters can automatically adjust to varying conditions in real time, improving the efficiency of harvesting and reducing the need for manual intervention**.** Handling Large Areas and Varied Conditions With 6G's high-speed connectivity, robotic harvesters can cover large areas with various terrain types and crop conditions, especially in rural areas where farming conditions can vary. By receiving real-time data from a network of sensors (e.g., moisture sensors, weather stations), harvesters can adapt their actions to suit different crops and environmental conditions, ensuring that the harvesting process is efficient regardless of the crop type or soil condition. Predictive Farming and Weather Forecasting 6G technology enables farmers to predict weather patterns and harvest conditions in advance. This predictive capability helps farmers plan their activities and make informed decisions regarding soil health and crop management**.** By accessing real-time weather data and advanced forecasting tools, farmers can anticipate weather-related challenges (e.g., drought, heavy rain) and take preventive actions, ensuring better yield and crop quality [29].

The advent of 6G technology in agriculture is set to enhance both crop production and quality. By leveraging the vast amounts of data gathered through advanced sensing and monitoring systems, **6G** makes it easier to make informed and timely decisions, which can significantly improve the efficiency and sustainability of agricultural practices.Beyond tillage, plant protection, UAVs, and harvesting, 6G technology also plays a critical role in various other aspects of agriculture, such as monitoring, marketing, and extension services. With its high-speed data transfer capabilities, 6G accelerates the use of cloud computing, digital platforms, and augmented reality, which contribute to more effective farm mechanization and better training and learning for farmers. Through real-time access to critical information, farmers can learn how to optimize their operations and make smarter decisions about resource management, crop health, and equipment use.Moreover, 6G technology simplifies the monitoring of environmental conditions, such as weather parameters, and enables quicker response to climate change signals. This is especially crucial in areas like hill agriculture, which remains underdeveloped and under-mechanized despite the availability of resources that could boost production. The ability to connect remote areas, including hill farms, via 6G networks could lead to greater mechanization advancements, improving agricultural productivity and reducing the dependency on manual labour. Another significant challenge in agriculture is food loss during the marketing and distribution phases.

It's estimated that food losses contribute to a significant portion of waste in the supply chain, with losses ranging from 2-20% in developing countries to 5-30% in developed nations. This loss is primarily attributed to inefficiencies in marketing and distribution. With 6G technology, rapid digital marketing solutions can be developed to streamline the sale, resale, custom hiring, and maintenance of farm equipment and produce. Speedy and efficient digital marketing can connect sellers and buyers more effectively, reducing waste and increasing profits. Ultimately**,** 6G technology brings a transformative potential to the agricultural sector by improving productivity, quality, and efficiency in both farm operations and food marketing, creating a more resilient and sustainable agricultural system [30]. 6G technology has the potential to revolutionize agricultural marketing by enabling virtual marketing platforms that rely on strong, global network connectivity. As a study from China revealed**,** 31.47% of farmers expressed interest in adopting 6G technology, highlighting the increasing demand for 6G among farmers and the agricultural sector. This indicates a growing recognition of the benefits of 6G in optimizing agricultural practices, from production to marketing. The scope of 6G in agriculture is vast, as it addresses a range of complex challenges, such as long production cycles, the need for diverse production methods, and numerous external factors influencing agricultural output. Achieving standardized production and management is difficult, but 6G has the capability to connect and streamline the entire agricultural process, making it more efficient and adaptable. One of the key areas where 6G can have a significant impact is in the agricultural supply chain. The supply chain spans across all stages of agriculture: before, during, and after production. To optimize this chain, it is essential to build a 6G-enabled network that links producers**,** retailers**,** distributors**,** and supplier**s** of agricultural products. This network would ensure the smooth flow of agricultural products from wholesale and retail markets to end consumers while connecting regulatory agencies and other stakeholders.

A robust 6G supply chain would not only integrate the movement of goods but also synchronize logistics**,** capital flow**,** and data flow**.** By combining these elements, 6G could improve the production**,** processing**,** and transportation of agricultural products, ensuring faster, more reliable, and more efficient delivery systems. This networked approach could lead to real-time tracking**,** better inventory management, and a more responsive supply chain**,** ultimately enhancing the efficiency and profitability of the entire agricultural sector [31]. While 6G technology promises to revolutionize agriculture, especially in terms of enhancing smart agriculture and its marketing, it also introduces certain challenges related to network infrastructure and costs. One of the primary challenges is the current limitation of internet connections, which makes it difficult for agricultural businesses, particularly shops and vendors, to share information quickly and efficiently. The advanced capabilities of 6G—such as very high speed, extremely high capacity, and ultra-low latency—are crucial for overcoming these limitations, facilitating real-time data transfer, and enabling advanced smart farming techniques. However, the transition to 6G brings with it significant costs. The demand for base stations and network management equipment is far higher than in 5G or 2G networks, which increases the financial investment required. The higher operational and maintenance costs of 6G networks also present challenges, especially for low-cost agricultural operations. Moreover, the increased infrastructure costs could be a barrier to widespread adoption of 6G in small-scale farming. Additionally, the transition to 6G may require the replacement or modification of current hardware and systems, which adds to the financial burden. The high utilization costs associated with 6G are another consideration when compared to the current 5G technologies. Another constraint is the limited range of 6G infrastructure—data transfer may be restricted over long distances, meaning that agricultural devices and machinery must be within close proximity to the 6G infrastructure for effective communication. This could be particularly problematic for large-scale agricultural operations with multiple machines spread across wide areas. Security is also a concern. With the advanced capabilities of 6G, it is crucial to build robust and reliable security systems to protect both service providers and end-users from potential vulnerabilities in the network. This will be essential to ensure that data is safely transmitted and that cybersecurity risks are minimized. Despite these challenges, the long-term benefits of 6G technology—including enhanced productivity, improved decision-making, better market access, and the ability to manage complex agricultural systems—are expected to outweigh the limitations. 6G will play a transformative role in shaping the future of smart agriculture, but addressing these barriers will be crucial for its successful integration.

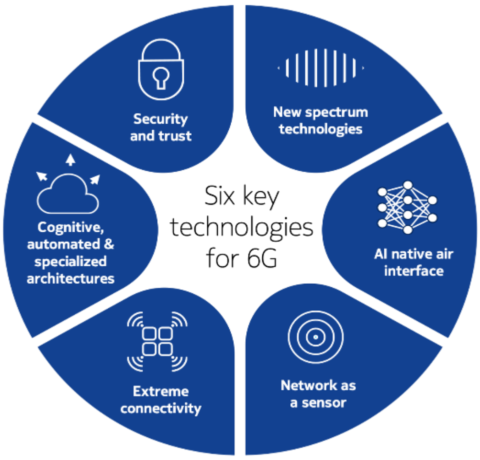

Figure 3. **Features of 6G technology**

Drones equipped with multispectral sensors are rapidly bridging the gap between satellite and ground-based remote sensing in agriculture. These drones are increasingly being used to assess the nutrient status of crops through digital soil mapping. With the help of AI algorithms, drones can detect issues such as pests, diseases, and weeds, allowing for targeted treatment with pesticides in specific areas after analyzing the data collected. This precise monitoring not only improves crop health but also helps in reducing the overuse of chemicals, thereby reducing the environmental impact.One of the major benefits of using 6G-powered drones is their ability to significantly reduce the use of chemical fertilizers and pesticides. It is projected that the use of chemicals could be reduced by 15% without affecting crop yields. This reduction in chemical use can help in cutting down the global emissions contributed by agriculture, aligning with stricter environmental regulations aimed at reducing soil nutrient losses and promoting sustainable farming practices.Despite the promising potential of 6G-powered drones in revolutionizing agriculture, there are some challenges. For instance, in areas with less than 0.4 hectares of land, the deployment of drones might not be as effective or economically viable, which could limit their widespread adoption in small-scale farming. Furthermore, the integration of 6G technology into these systems requires significant investment in infrastructure and the necessary skills to operate and maintain these advanced systems, which may pose challenges for farmers in resource-constrained settings. This element has to taken into consideration even as implementing the 6G answers in agriculture incorporate generation to make farm to market greater wi-fi-wireless scientific wireless and effective. Clever agriculture referred to as ag-tech uses IoT sensors to connect the whole lot from irrigation structures to soil and animal manufacturing. As 6G rolls out international, this excessive-bandwidth cellular generation is poised to make an impact on ag-tech. Ag-tech seeks to maximise meals production by way of empowering farmers with the information they need for suitable organization selections. Associated ag-tech answers help farms. Clever uses wi-fi wireless sensors to reveal plant growth in its greenhouses. Aggregating statistics from many places permits them to beautify boom protocols, yielding healthier vegetation and a exceptional harvest. From orchards to cattle ranching, farms are using IoT answers to show a couple of drivers affecting their bottom line, together with: Temperature, Soil conditions, Contaminants and Water. wi-fi wireless and cell packages might also moreover require mobile IoT connectivity to permit far off data collection and tool control. The ones skills are similar to a production setting in which the complete technique can be monitored. These days, a few smart farming endpoints depend on brief-variety wi-fi wireless era, which includes and Bluetooth. Others use mobile due to distances and RF coverage desires.6G will permit new programs and increase or update short-variety ones. An instance is the use of video-equipped drones to reveal crop conditions and livestock health. 6G technology holds first-rate promise for centralized records aggregation in huge farming operations. A massive corporate farm could construct a private 6G network to aggregate facts from micro-monitored crop management systems. These structures encompass soil moisture sensor density, likely masses instances denser than what to be had technologies help. This network can allow a greater green actual-time tracking gadget with triggers for throttling irrigation and other crop help systems.

Table 1. Networks Through Time

Generations	Applications	Bandwidth	Download speed	Upload speed
1	Vocalization	Analog	2Kb/s	
2	Vocalization and data	25 MHz	236 Kbps	236kbps
3	Vocalization, Metrics ,GPS & Video Calling	25 MHz	21Mbps	5Mbps
4	Vocalization, Metrics, Video Calling, HD Television, & Online Gaming.	100 MHz	1Gpbs	500Mbps
5	Vocalization, Metrics, Video Calling, Ultra HD video, Virtual Reality applications	30–300 GHz	2.5Gpbs	1.2Gbps
6	Augmented (AR), Virtual reality (VR)	410MHz – 7.12GHZ	200Tbps	938Gbps

6G facilitates data aggregation, allowing large-scale industrial farms to more effectively utilize predictive analytics. By analysing both historical and current data on conditions, farms can make more informed decisions, Analytic software develops models and forecasts to assist farmers in making informed decisions some farmers are using drones to reveal their vegetation. Drones are much less costly than riding tractors through fields and offer greater targeted information about crop harm and different variables. As a excessive-bandwidth technology, 6G will allow drones to accumulate better-first-rate video information and convey it quicker. This excessive-speed facts transmission capability will enable AI drone technology improvement and real-time reviews. autonomous Agricultural cars: growing self sustaining vehicle technology in different sectors will translate to farm implements. Already, tractors with on board computer systems allow operators to manipulate minute farming project info (e.g., the distance among seed rows and stress exerted on them as they're planted in the floor). Driverless farm equipment will enhance to offer greater flexibility and performance for farmers and shop on exertions costs. Vehicles for crop transportation can reap IoT sensor blessings as well. These sensors can song cargo temperature and ship indicators if it becomes too warm or cold (i.e., cold chain). Small mobile sensors such as asset trackers will possibly continue to use high latency technology like LPWAN. 6G will permit. autonomous cars with extra powerful on board computer systems to send and obtain larger, ultra low latency facts streams, which includes video. weather Stations Farming operations are at the weather's mercy. Farmers can lose massive crop quantities to preventable illnesses and damage. Connected climate stations inside the subject can remedy this predicament, offering farmers with subject situation records. One instance is the In field tracking device, evolved via AMA devices. Infield measures soil humidity and texture, air temperature, wind speed, and solar exposure. Deployed in faraway fields, climate stations will probably continue to make use of LPWAN connectivity for the instant future. They will gain from 6G, as it will create greater data dense observation and area computing. learn the way AMA instruments leverages mobile connectivity to maximize farming yields. as the cellular-related world transitions to 6G, clever farming will continue to extend. information and predictive analytics will permit farmers to make picks yielding more productivity and efficiency.

The global outcomes will be sustainable farming practices prepared to feed growing populations. An entire new method to leveraging the discipline. There are numerous key factors using the problems in 21st-century meals production .The Demand is rising at the same time as herbal resources decrease. Food safety is a growing project in the face of weather trade. plants are extraordinarily at risk of climate change. plants are extremely prone to greenhouse gas emissions, which increase international temperature, increase pest and weed infestation, and regulate precipitation styles. All of those demanding situations can result in reduced crop yields. Moreover, as weather exchange impacts the land and weather; the global populace is expected to increase to over nine billion humans via mid-century.no matter this developing need to thoroughly feed humans, meals waste is a great problem, with handiest 14% of food produced achieving clients. How satisfactory to put into effect practices to reduce food waste is up within the air, and there are barriers at every degree of the deliver chain from the farmer to the patron. issues encompass keeping and packaging meals, transportation, grocery store shelf existence, consumer demand or even customer meal planning. More than years into the pandemic, we're seeing rising prices at the grocery save because of inflation, high patron demand and disruptions in deliver chains. Interrupt offerings, greater people to feed with fewer herbal sources and guide labour require wondering outside the container, which is paving the way for 6G in agriculture.

Table 2. Comparative Analysis Table

Aspects	5G Technology	4G Mobile Networks	Drones	LoRaWAN
Effectiveness	High potential for precision agriculture, real-time monitoring, and automation, leading to	Enables access to market information, weather updates, and extension services,	Provides aerial insights for crop health monitoring, disease detection, and precision spraying	Suitable for longrange, low-power monitoring of environmental
Efficiency	High initial infrastructure investment and device costs	Relatively lower infrastructure and device costs compared to 5G.	High initial investment for drone purchase and training	Low infrastructure and device costs. *Operational costs are minimal due to low power consumption
Scalability	Requires extensive network infrastructure rollout, particularly in rural areas.	Relatively good scalability due to existing 4G infrastructure.	Scalability is limited by the operational range and battery life of individual drones.	Highly scalable due to low-power and long-range communication capabilities
Implementation	Requires significant infrastructural development and technical expertise	Relatively easier to implement due to existing infrastructure and user familiarity	Requires trained personnel for safe and effective operation	Easier to implement due to minimal infrastructure requirements

A few agencies are growing smart farming structures that may benefit from 6G, AI and part computing, generation with 6G may even make farming extra unique, the use of customized, data-driven techniques to farm manipulate in place of previous, one-duration-fits all questioning for crop yield, water and pesticide use, and waste manage. In agriculture 6G expertise the capacity of clever agriculture is evolving, and speedy. With the advent of 6G generation and acceleration in digital transformation at some stage in the organisation, there are new possibilities for farm control systems to perform with extra accuracy and less waste. The one upgrades are had to sustainably feed the planet's growing population, Precision farming with 6G ought to help optimize sources, reduce water consumption, and enhance productivity. So how will it rework the wider agriculture business enterprise. With the ability for 6G to create new sales models all through a multitude of sectors together with automobile and manufacturing, use instances in agriculture offer many exciting prospects for the future of smart farms and their abilities to harness the value of records. Smart agriculture is a control idea focused on providing the rural enterprise with the infrastructure to leverage advanced generation which includes large information, the cloud and the internet of things (IoT) for monitoring, monitoring, automating and analysing operations. As wearable's grow to be less steeply-priced and 6G makes it simpler to scale networks containing large numbers of IoT devices, fitness tracking for livestock can also emerge. With more correct fitness information, farmers can lessen the use of antibiotics with out compromising the safety of the meals deliver. Nowadays's farms are leveraging a huge range of internet of factors (IoT) gadgets to assist growers limit operation fees, increase yields and provide higher visibility in an unpredictable environment.

In fact, almost 12 million agricultural sensors are forecasted to be established globally by means of 2023. 6G is expected to kick things up a notch with the aid of helping extensively faster net speeds (asa whole lot as one hundred times faster than 5G), enabling gadget getting to know and close to actual-time communique among gadgets and the cloud. Agricultural authentic gadget manufacturers (OEMs) can gain from automated farming processes enabled via next generation 6G answers, remotely collecting and reading wealthy statistics from their machines and terrain. Making use of 6G technology a extensive range of better technologies will divulge heart's contents to farmers. Subject situations can be extra appropriately monitored via a larger network of records-amassing sensors self sustaining drones can scan vegetation the use of AI to identify weeds and practice pesticides with precision. more crucially, farmers can better understand their water consumption and practice adjustments to irrigation structures primarily based on accurate statistics. progress is picking up pace round the arena, with projects like the 6G Open Innovation Lab inside the US trying out and developing use instances at the ground.The early ranges of 6G have centered on permitting excessive-bandwidth connectivity. before 6G infrastructure will become extra ubiquitous, centralized farms will be the maximum sensible use instances.

A massive corporate farming operation might construct a personal 6G community to permit high-bandwidth use instances (e.g., crop tracking using drones) and aggregation of information from lots of transactional or triggered IoT sensors. Now, 6G might be maximum leveraged when a farming operation utilizes big quantities of facts from disparate assets. On an industrial hen farm, statistics from thermostats and feeding machines come to a critical connection factor. every of these thousands 306. of sensors generates small information quantities for too little fee or complexity for a broadband-grade 6G statistics pipe. when aggregated in properly dimensioned clusters, the resulting bandwidth can align with 6G cell broadband bandwidth. 6G is an super approach to aggregate and backhaul this information.we are able to anticipate 6G 3GPP launch (Rel) 17 to empower big IoT in 3 to five years. Rel 17 will enable builders to leverage the usual for low-energy gadgets working on the 6G New Radio (NR) radio get admission to network (RAN). whilst this occurs, records aggregation over quick-variety radio technologies can be mitigated considering the fact that low-value, low power sensors can operate on low-power 6G NR modems. Over the subsequent five to 10 years, lower LTE categories (i.e., NB-IoT and LTE-M) will play a main role in connectivity options for far flung agricultural sensors. as the technology evolves, strength needs and costs will drop, permitting new designs and ideas for far off agricultural sensors. As 6G standards increase, the cease-to-give up potential to bridge technology becomes extra seamless. future agriculture different generation in with 6G will offer seamless coverage in far off areas throughout the energy efficiency, spectrum efficiency and community performance. 6G will also usher inside the ear of generation advance, such as virtual truth (VR), Augmented fact (AR) and more.

In particular 6G, is expected to help farmers make better use to display climate, actual-time costs, world traits, and livestock, amongst others. A key beneficiary of 6G era is the agriculture quarter. Using technology has the capacity to elevate this to 50% or greater. Being a zone that relies on robust networks and connectivity with special components , it's far vital for all stakeholders to have a seamless connection to deliver a customized provider. With the proper connections in area, farmers can obtain well timed facts on government services, suitable plants as per season, track markets for first-rate pricing, and the capacity to take part in exchange-associated activities. moreover, via the usage of clever farming and precision agriculture, stakeholders can revel in elevated productivity and efficiency inside the complete farm-to market system. With this, the world can witness a upward thrust in pastime, in the long run contributing to elevated GDP boom through BW business word October08, 2022. in keeping with a U.N. organisation document, 38 in keeping with cent of the Earth’s land changed into used for agricultural functions such as for cropland and grazing livestock. whilst a great deal of now a day’s 6G infrastructure is being deployed in dense city environments, coverage in rural areas is developing. 6G will permit opportunities for OEMs and actors throughout the agricultural zone to capture greater price. Enhance the effectiveness of farming practices, innovations across the farming quarter may be needed to meet the worldwide food demand for a growing populace. 6Genabled solutions will help facilitate the virtual transformation of agriculture, and at the same time as the enterprise has been slower to adopt new technologies, the possibilities of smarter farming techniques are understandably thrilling. with the aid of turning in innovation in modern-day agriculture, Cubic Telecom’s connected software program answers permit OEMs and enterprise gamers to optimize their farm management systems. With the global smart agriculture market anticipated to be really worth $15.three billion by using 2025, the possibilities for stakeholders are sizable.

4. Conclusion

Challenges must be carefully addressed, with appropriate policies in place to fully realize the benefits of 6G technology. This requires collaboration between network operators, governments, and farmers. Technological advancements and integration with advanced connectivity networks are key to the successful adoption of this technology. With improved farm mechanization, issues such as food security, labour shortages, and environmental sustainability can be mitigated. Following the transition to 6G technology, future smart agriculture will feature seamless operations, precise production, optimized cultivation, standardized outputs, and intelligent oversight. 6G’s low latency, high data transfer capabilities, and extensive connectivity enable the widespread deployment of IOT in agriculture. As noted, 6G applications in farm mechanization are expanding, and these can be further elevated through grassroots digitalization. In conclusion, 6G will play a crucial role in enhancing agricultural production through farm mechanization, setting the stage for future growth and adoption. This also lays the foundation for upcoming 7G and 8G applications.

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