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Review

6G-Enabled Smart Agriculture: A Review and Prospect

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Abstract: As human society develops, the population is growing explosively and water and land resources are gradually being exhausted due to pollution. Smart agriculture is regarded as having an essential role in addressing the above challenges. Smart agriculture can significantly improve the agro-ecological environment and the yield and quality of agricultural products, and it can reduce the usage of pesticides and chemical fertilizers, thus alleviating the pollution of farmland and improving the sustainability of agricultural activities. The key to smart agriculture is in utilizing information and communication technologies to make agricultural cultivation and production automatic and intelligent. Specifically, wireless communications play an active role in the development of agriculture, and every generation of wireless communication technology drives agriculture to a more intelligent stage. In this article, we first review the wireless technologies which have mature applications in agriculture. Moreover, it is of importance to exploit the up-to-date communication technologies to further promote agricultural development. Therefore, we have surveyed the key technologies in sixth-generation mobile communication systems, as well as their existing and potential applications in smart agriculture.

Keywords: 6G; smart agriculture; space–air–ground integrated networks; terahertz technology; wireless AI; integrated sensing and communication; advanced MIMO technology

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1. Introduction

Agriculture is the foundation of human society. It plays a vital role in maintaining social stability and promoting other industries. However, traditional agriculture is labor intensive and inefficient in resource utilization, and it is not environmentally friendly enough. This makes it hypodynamic to cope with problems such as explosive population growth, climate extremes, and resource shortages, which is therefore imperative for the evolution of agriculture technology. As summarized in Table 1, agriculture has gone through four stages (i.e., from agriculture 1.0 to agriculture 4.0), wherein agriculture 4.0 is also known as smart agriculture (or precision agriculture) [1]. The concept of smart agriculture, which was initiated in 2017, is defined as the deep integration of modern science and technology with agriculture so that agricultural cultivation and production can be unmanned, automated, and intelligent [2].

Wireless communication technologies are essential for the realization of smart agriculture. Nowadays, various mature wireless communication standards and systems have been widely applied in agriculture [3], e.g., ZigBee LoRa, RFM69, Bluetooth, Narrow Band IoT (NB-IoT), SigFox, Wireless Fidelity (Wi-Fi), and WiMAX. Their main applications include smart irrigation, pest detection, soil sensing, greenhouse environmental control, plant protection, etc. [4], which can make crops safe from pests and lack of nutrients, automate water and lighting, and prevent forest fires, and, in fisheries, they can prevent hypoxia. However, the aforementioned applications of wireless communication technologies in agriculture are very limited. Moreover, the above technologies do not offer a good solution in the face of more serious challenges in terms of population, resources, and the environment. In order to achieve highly automated, intelligent, and sustainable agriculture, the utilization and integration of more advanced wireless communication technologies are necessary. The motivation of this review is to provide a reference for the future direction of agriculture by introducing several 6G technologies and exploring their applications in agriculture. The review of existing works mainly focuses on the agricultural applications of wireless communication technologies that are well developed [5]. As for emerging 6G technology, the current literature has mainly investigated the application of a particular technology in agriculture. To our best knowledge, there is no work available that discusses 6G technologies and their application in agriculture as systematically as we do in this review.

The main contributions of this article are the following:

1. We introduce the history of agriculture and the concept of smart agriculture.
2. We review several wireless communication technologies widely used in agriculture and their specific application scenarios and cases in agriculture.
3. We introduce several up-to-date 6G technologies and discuss their characteristics, advantages, and limitations from the perspective of agriculture. Then, we survey the current applications in agriculture activities from the existing literature. Furthermore, the potential applications of 6G technologies in agriculture are also envisaged.

Table 1. The development process of agriculture.

Name	The Beginning Period	Features
Agri 1.0 [6]	16th Century	The labor force is mainly human and animal, and the means of production are inferior. This has led to small farms and low levels of production.
Agri 2.0 [7]	1765	The upgrading of the steam engine leads to the mechanization of agricultural tools, which significantly increases productivity.
Agri 3.0 [8]	1992	Information and communication technologies begin to be used in agriculture. The production and cultivation of agriculture is partially automated.
Agri 4.0 [9]	2017	Advanced information and communication technologies (Artificial Intelligence) are being used in-depth in agriculture, with agricultural cultivation and production becoming highly unmanned and intelligent.

2. Mature Wireless Communication Technologies Used in Agriculture

Nowadays, there is a plethora of wireless communication technologies widely used in agricultural activities, improving crops' quality and yield, saving resources, and protecting the environment. In the following, we detail several mature wireless communication technologies (e.g., ZigBee, LoRa, Wi-Fi, and Bluetooth) and their applications in agriculture, and we show the importance of wireless communication technologies to agriculture (summarized in Table 2).

Table 2. Mature wireless communication technologies in agriculture.

Name	Low Costs	Low Power Consumption	Easy Deployment	Information Transmission Distance	Information Transmission Rate	Operating Frequency Bands	Specific Application Cases
ZigBee	√	√	√	10~100 m	20~250 Kb/s	Global Band: 2.4 GHz European Band: 868 MHz North American Band: 915 MHz	Environmental monitoring in Qiongzhou University Botanical Garden, Hainan Province [10]; smart irrigation in southern Algeria [11]; and decertation monitoring in Brazilian farmland [12].
LoRa	√	√	√	2~15 km	10~220 Kb/s	European Union: 868 MHz North America: 915 MHz China: 783 MHz	Environmental monitoring of vineyards on the UTAD University campus [13]; tree growth status monitoring in tree plantations in Indiana, USA [14]; and an intelligent irrigation system applied in Indian farmland [15].
Wi-Fi	√	√	√	5~300 m	125 Kb/s~4 Gb/s	2.4 GHz, 5 GHz, 6 GHz	Providing communication services for the countries in Ghana [16]; soil salinity monitoring in Suntai and Dongxin [17]; and intelligent irrigation systems applied in the semi-arid region of southeastern Spain (Murcia region) [18].
Bluetooth	√	√	√	8~30 m	100 Kb~50 Mb/s	2.4 GHz	Smart seeders deployed in Indian farmland [19]; wireless sensor networks for crop growth monitoring by agronomists in Ukraine [20]; and wireless sensor networks for cattle behavior monitoring in Romania [21].

2.1. ZigBee

ZigBee is a wireless communication technology based on the IEEE 802.15.4 standard, operating in the ISM (Industrial, Scientific, and Medical) band at 2.4 GHz with a transmission rate of 25–250 kb, which is typically used for sensor control in small areas [22]. ZigBee is very suitable for many fields of agriculture due to its advantages of low cost, low power consumption, low latency, and easy deployment. Specifically, ZigBee has many applications in agricultural wireless sensor networks. Lin et al. [23] applied ZigBee technology in a greenhouse detection system, with the objective of obtaining real-time environmental information such as temperature, humidity, and lighting. The system was beneficial in keeping crops in their optimal growth conditions. Xiang et al. [24] proposed an automatic drip irrigation system consisting of a ZigBee-based wireless sensor network and a fuzzy controller. The system collects soil moisture, temperature, and other information, which is then fed to a fuzzy controller to decide whether to drip irrigate or not. Ding et al. [25] designed a distributed heterogeneous wireless sensor network based on ZigBee technology for the monitoring and regulation of the agricultural environment. Through more precise control of the agricultural environment, the management of a farm is effectively improved.

2.2. LoRa

LoRa is a wireless communication technology with several standards (which are different in China, the USA, the EU, and Japan). LoRa works in the ISM band (USA: 915 MHz, EU: 433 MHz, and 868 MHz) with a transmission rate of 10 kb/s, which is generally employed for military communication due to its long transmission distance [26]. The advantages of LoRa lie in, e.g., its low power consumption, long transmission range, low cost, and flexible deployment, which makes it suitable to be applied in agricultural cultivation and production. Ma et al. [27] developed a LoRa-based wireless sensor network and applied it to both environmental monitoring and wireless communication. With the designed wireless sensor network, the management of the studied farm was greatly enhanced. Swain et al. [28] applied LoRa to specific low-power hardware platforms to make a resource-efficient sensing system that can monitor farmland on a large scale. Yang et al. [29] designed a LoRa-based greenhouse environmental monitoring system with remote manipulability and low power consumption. The system can monitor and collect soil and environmental parameters and control lighting, cooling, and irrigation.

2.3. Wi-Fi

Wi-Fi is a wireless local area network technology based on the IEEE 802.11 standard, and it operates in the 2.4 Ghz and 5 Ghz frequency bands. The latest Wi-Fi 7 technology, which was released in 2022, is based on the IEEE 802.11 standard, and it operates in the 2.4 GHz, 5 GHz, and 6 GHz bands [30]. Wi-Fi is the most widely used wireless technology and is generally intended for internet access, offering a wide range of bandwidths, low power consumption, and high transmission rate and allowing for long-distance communication. Antenna technology is crucial for Wi-Fi. Kulkarni [31] designed a novel monopole antenna for Wi-Fi with strong radiation. An antenna technique with high array gain and radiation efficiency that meets the bandwidth requirements of Wi-Fi 5 and Wi-Fi 6 was proposed in [32]. As for its application in agriculture, Wi-Fi is commonly utilized for wireless sensing, video surveillance, and communication in remote areas. For example, Lloret et al. [33] investigated a Wi-Fi-based sensor network that helps farmers find the best time to irrigate their farmland by measuring environmental information such as temperature, humidity, and soil salinity. Ahmed et al. [34] designed a Wi-Fi-based, scalable, low-latency network architecture that can communicate over long distances, which is well suited for farm monitoring and control in remote rural areas. By exploiting the wide bandwidth and high transmission rate of Wi-Fi, Li et al. [35] designed a video surveillance system suitable for agriculture that can be used to monitor plant pests.

2.4. Bluetooth

Bluetooth is a wireless technology that allows data and voice to be transmitted over short distances. It operates in the ISM band at 2.4 GHz. The latest Bluetooth, 5.2, has a data transfer rate of over 50 Mbps [36]. Bluetooth is generally used for data transfer between various end devices, and it operates in a globally uniform frequency band and is highly resistant to interference and, therefore, suitable for a wide range of devices. The applications of Bluetooth in agriculture are mainly focused on environmental monitoring and intelligent irrigation. Shaobo et al. [37] proposed a novel environmental control system that collects data on the farm environment and transmits information on environmental parameters via a Bluetooth chip in a mobile phone. This system is very convenient for farmers as it allows monitoring and setting farm environmental parameters simply by using a mobile phone. Bjarnason et al. [38] invented a sensor system using BLE (Bluetooth low energy) technology to monitor temperature and humidity. The system has a long standby time due to the ultra-low power consumption of BLE. It is very suitable for remote areas, such as farmland at high altitudes where electricity is not readily available. Hong et al. [39] proposed a sensor system based on a Bluetooth module to achieve intelligent irrigation. The system collects environmental information such as soil moisture and uses the collected information to measure whether the farmland needs to be irrigated, enabling the efficient use of water resources. Compared with a conventional irrigation system, the proposed system can save more than 90% water and electricity.

As can be seen from the above applications, utilizing wireless communication technologies in agriculture can enable a high degree of water conservation in agricultural cultivation and production, the precise monitoring of the agricultural environment, and the effective prevention of plant diseases, which undoubtedly shows a significant step forward compared to traditional agriculture. However, each technology has its own limitations, such as the short transmission distance of ZigBee, the low data transmission rate of LoRa, unguaranteed quality of service in Wi-Fi networks, and the security issues of Bluetooth. These drawbacks have led to significant limitations in applying the above wireless communication technologies in agriculture, making them unable to support more complex and large-scale agricultural activities (e.g., plant pest detection, food safety testing, etc.). In order to drive the intelligent transformation of agriculture, more advanced communication technologies are essential. In the next section, we will introduce several key 6G technologies and detail their existing and potential applications in agriculture.

3. 6G and Its Associated Technologies in Agriculture

With millions of 5G (the fifth generation of mobile technology) base stations in place, 5G has entered the market for mass commercialization. However, 5G still has some limitations [40]. One issue is the very high cost of 5G infrastructure. Base stations for 5G have a much smaller coverage area compared with 4G base stations. Thus, more base stations are required to achieve full coverage in a 5G network. The other issue is the security for parts of 5G technologies. For example, software-defined networks (SDNs) lack the mechanisms for trust verification between management applications and controllers. Moreover, the main network structures in 5G, e.g., heterogeneous networks (HetNets), are limited to ground-based networks. As a result, China, the EU, and several other countries have begun to explore 6G, which will open up a new era of connection, intelligence, and sensing. It will drive a comprehensive digital transformation of all industries, integrating the physical, biological, and digital worlds [41]. As such, it is foreseeable that 6G technology will have the potential to drive the development of smart agriculture even further. In the following, we review the associated technologies of 6G and explore their existing, as well as potential, applications in agriculture (see Table 3 and Figure 1).

Table 3. 6G technologies in agriculture.

Name	Features	Existing or Potential Applications	Limitations and Challenges
Space–air–ground-integrated networks	Integration of ground-based, air-based, and space-based networks. Providing large coverage, high throughput, and strong resilience.	Enhancing farm management. Forest protection. Supporting communication in remote areas.	Infrastructure cost for drones, satellites, and base stations in agricultural scenario needs further investigation.
Terahertz technology	Wide bandwidth, low latency, high transmission rate, strong penetration, and high sensitivity.	Pesticide residue monitoring. Plant nutrition monitoring. Grain quality monitoring. Weather forecasting.	A terahertz wave attenuates very quickly, and so the coverage area is restricted. A large-scale farm is a challenging scenario for its application.
RIS	Low cost, low energy consumption, programmable, easy to deploy, and intelligent reconfiguration of the wireless propagation environment.	Enhancing agricultural communication networks in terms of coverage and energy efficiency. Enhancing precision agricultural sensing.	RIS is currently not industrialized. Therefore, it still requires experiments and evaluation for its application in various agricultural activities.
Wireless AI	Global optimization for multi-models and end-to-end communications. Efficient approximation and fitment for arbitrary complex systems. Continuous self-adjustment/evolution/repairment in a variety of scenarios and applications.	AI-based agricultural sensing network design. Resource management for agricultural networks. AI-based wireless sensing for agricultural activities.	In the current agricultural applications, AI and wireless communication technology are simply combined together, and there is no actual improvement of wireless communication performance by utilizing AI.
Integrated sensing and communication	Integration of sensing and communication functions. High efficiency of spectrum/hardware utilization and information processing.	Millimeter wave-based ISAC systems for the prevention of plant diseases/infestations and for dairy farming. ISAC with space–air–ground-integrated networks for forest protection.	It is still in the design stage for prototypes and is not standardized and industrialized. The complex environment in some agricultural scenarios may simultaneously degrade its communication and sensing performance.
Massive MIMO	Ultra-large antenna arrays and higher spectral efficiency, supporting more flexible network architecture.	Supporting agricultural IoT for large-scale and complex agricultural activities. Enhancing space–air–ground-integrated communication networks for agriculture. Precision agricultural sensing, e.g., earthquake prediction and accurate harvesting.	The complexity of massive MIMO deployments increases rapidly with the number of antennas and users, making its hardware requirements high. Hardware impairment and pilot contamination are issues that should be carefully handled.

Table 3. *Cont.*

Name	Features	Existing or Potential Applications	Limitations and Challenges
Digital twins	Digital replicas of actual physical systems. Enabling high-level control of physical entities. Management of complex systems.	Conditioning for plant growth. Greenhouse environment settings. Design of novel agricultural systems.	There is a lack of standard reference for the research and implementation of key digital twin technologies in agriculture, which leads to poor compatibility and interaction between products developed by different digital twin teams and makes data integration difficult.
Ambient backscatter communications	Low energy, low cost, easy to deploy, and mature development.	Plant leaf moisture monitoring Greenhouse temperature monitoring UAV communication performance improvement	The transmission range of backscatter communication is limited. It is not suitable for long distance communication and large-scale sensing.

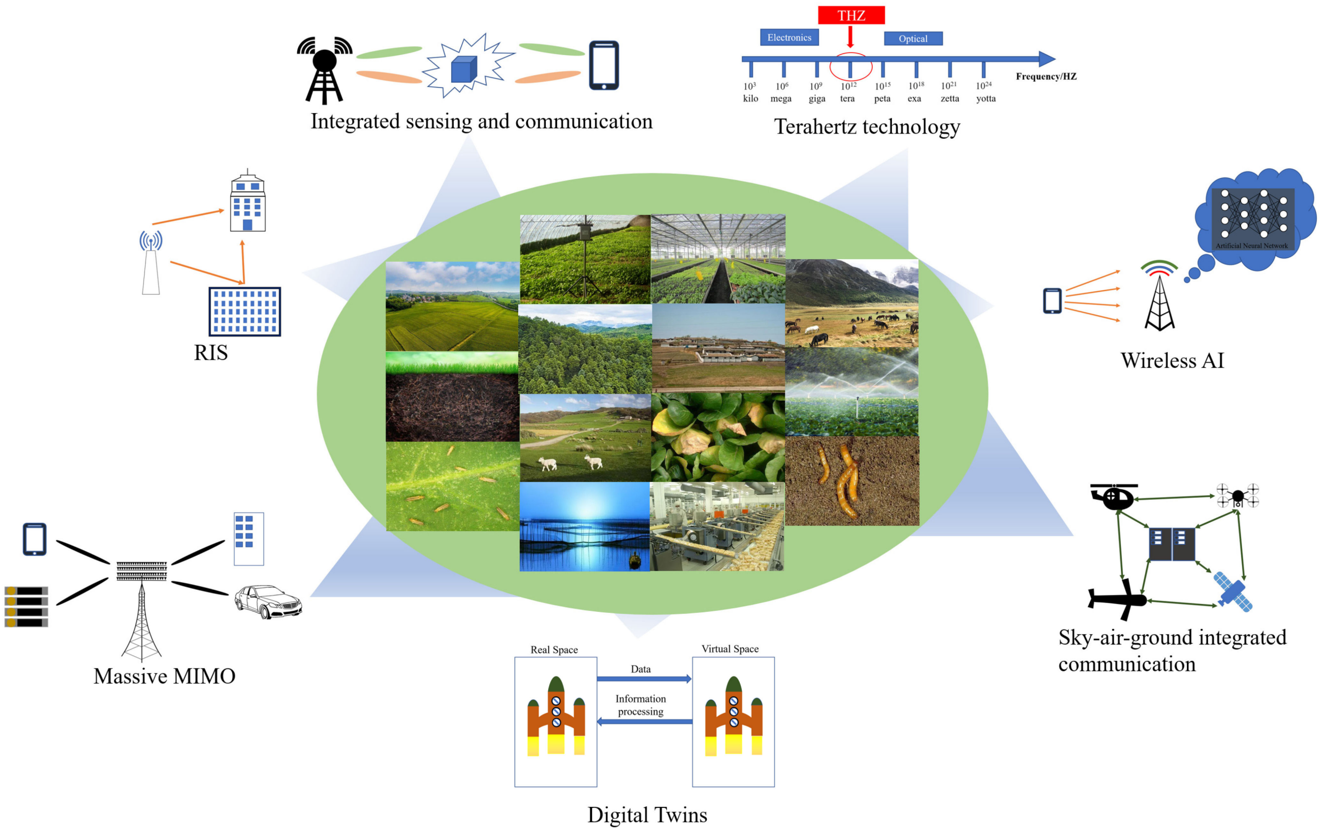

Figure 1. Sixth-generation technologies in agriculture.

3.1. Space–Air–Ground-Integrated Networks

With the development of human society, the scope of human activities is expanding, and they are no longer limited to the ground, but now include the ocean, mountains, the sky, space, and the abyss. As a result, it is hardly possible to meet the challenge of ubiquitous coverage with terrestrial communication networks alone. Meanwhile, various applications have recently emerged that require multi-dimensional networks, such as autonomous driving, smart cities, interplanetary communications, disaster rescue, etc. [42]. Therefore, the idea of an integrated space–air–ground network has been initiated. In the 6G era, space-based (with high-/medium-/low-orbit satellites) and air-based (with airborne-/high-/low-altitude aircrafts) networks will be deeply integrated with ground-based cellular/Wi-Fi/wired networks, which can provide ubiquitous coverage on the surface, as well as in three-dimensional space (see Figure 2). Specifically, the integrated space–air–ground network aims to achieve the omni-directional integration of ground and non-ground networks on the physical, link, network, and system levels from the perspectives of hardware, software, protocols, and services. Through the deep convergence of multi-dimensional networks, the integrated space–air–ground network can effectively incorporate various resources, perform intelligent network control and information processing, and efficiently handle various network requirements. Thanks to the application of AI, the performance of space–air–ground-integrated networks has been significantly improved in many aspects. Combining AI with space–air–ground-integrated networks has now become a hotspot in academia [43–45].

As an essential component of aerial networks, the unmanned aerial vehicle (UAV) has been used in agriculture for a long time. For example, UAVs have been combined with Artificial Intelligence to make pesticide spraying more efficient [46]. UAV networks have been used to provide wireless communication services to disaster areas [47]. By introducing fog computing technology, UAV networks have been applied to improve the efficiency of forest fire monitoring [48]. As for space-based networks, satellite systems also have a wide application in agriculture, for instance, high-resolution satellites for soil and crop information diagnosis [49], weather prediction using satellites to detect temperature and humidity at high-altitude areas [50], and crop yield prediction by remote sensing using satellite imagery and unsupervised learning [51].

An integrated space–air–ground communication network consisting of base stations, drones, and satellites can better aid agricultural activities by complementing the advantages of various networks. For example, Feiyang et al. [52] integrated multiple members such as satellites, drones, and agricultural wireless sensor networks to construct a terrain-independent laboratory, allowing for rapid (less than two hours) and detailed monitoring with higher efficiency and field analysis ability compared to traditional schemes. Almalki et al. [53] designed a low-cost integrated monitoring platform to collect environmental parameters based on the combination of UAV and IoT technology, which allows the automatic and real-time monitoring of an environment using above-ground and underground sensors. The platform can therefore help farmers predict environmental data over large farmland areas, leading to improved crop quality and yields. Mengen et al. [54] invented a novel IoT using radar, drones, and satellites for the measurement of soil and plant parameters. The authors demonstrated that the new platform has a high measurement accuracy and can be used for various crop types. Fourati et al. [55] addressed the challenge for network communication in rural areas through utilizing Artificial Intelligence to integrate space, air, and ground networks. The proposed framework can effectively improve network connectivity and reduce the cost of rural communication.

An integrated space–air–ground network is robust because it combines space-based, air-based, and ground-based networks. It is believed that an integrated space–air–ground network can have additional applications in agriculture. Specifically, it can meet the demand for communication in rural areas and high-resolution imagery and expand the range of IoT applications in agriculture. In the following, we list some of its potential applications.

(1) Island farm communications: Island farms are generally in remote areas and operate on a large scale. Deploying base stations and other communication network infrastructure is costly and unprofitable, whereas air–ground-integrated networks are suitable for remote areas and large areas.
(2) Implementing large-scale and complex agricultural activities: Agricultural production and cultivation activities inevitably tend to be large-scale and complex, and it is challenging to satisfy large-scale and complex agricultural activities with ground networks alone, while air–air–ground-integrated networks intelligently integrate ground communication networks, drones, and satellites to flexibly build communication networks that fully meet the needs of large-scale and highly complex agricultural activities.
(3) Forest protection: Forests generally cover large areas and are located in remote areas with complex terrain. Solely using ground-based infrastructures to provide full coverage in forests is not only costly, but also inefficient. A deep combination of drone and satellite networks can support the wireless sensor networks for monitoring in forests, thus preventing incidents such as forest fires.

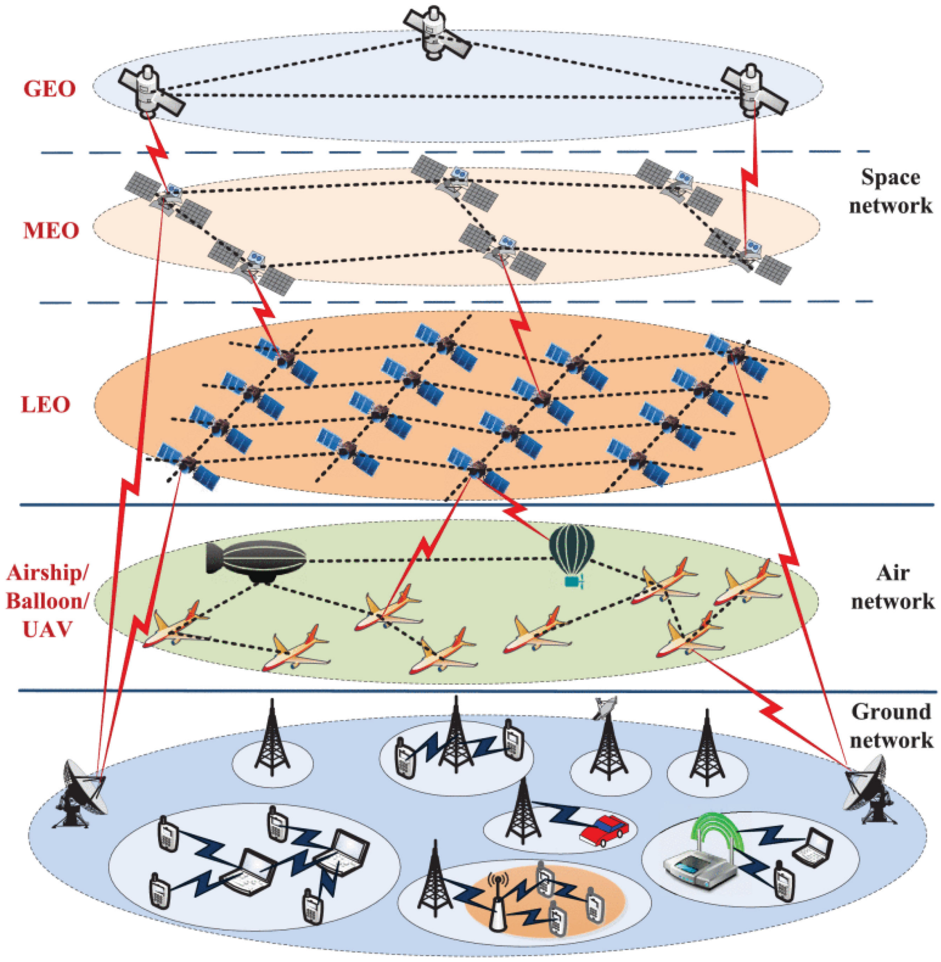

Figure 2. An architecture for space–air–ground-integrated network [56].

3.2. Terahertz Technology

With the development of information technology, there has been an explosion in wireless data traffic. Some studies have shown that wireless data traffic doubles every 18 months [57]. From 2016 to 2021, mobile data traffic grew by seven times, while video traffic grew by three times in the same period [58]. Under the above background, communication technologies operating on higher frequency bands are no longer rare, e.g., millimeter wave communications of below 100 GHz [59]. However, it is still struggling to support the communication of billions of communication devices and data transmission at the Tbps level. Terahertz communications have been proposed as a potential solution to these problems due to its favorable features of an ultra-high bandwidth, extra-low latency, and super-high data transfer rate. Terahertz (THz) waves lie in the frequency band from 0.1 THz to 10 THz (see Figure 3). This band is located between the microwave and infrared bands on the entire electromagnetic spectrum. Therefore, terahertz waves have both the penetrating and absorbing properties belonging to the microwave band and the properties of spectral resolution. Terahertz communication is a technology that uses the terahertz band as a carrier wave for wireless communications. The terahertz band has a large number of bandwidths available to support ultra-high communication rates. As a result, terahertz communications are considered an important alternative radio technology for achieving 6G terabits per second (Tbps) communication rates, and they are expected to be used in scenarios such as holographic communications, micro-sized communications, data return with ultra-high capacity, and short-range ultra-high-rate transmissions. In addition, the high-precision positioning and high-resolution sensory imaging of networks and terminal devices are also possible extensions of terahertz communications due to the large bandwidth of terahertz signals [60].

Unlike other 6G key technologies, research on terahertz technology started over a decade ago. Terahertz technology is used more widely in agriculture than other 6G technologies. Zahid et al. [61] conceived a system to measure the water content in leaves and detect the presence of pesticide residues in leaves using terahertz technology. This work initiated the applicability of terahertz bands in sensing the quality of plant life. Usman et al. [62] proposed an integrated communication sensing system for plant health detection using terahertz technology, which can monitor plant nutrients at the nanoscale for the early detection of agricultural diseases or malnutrition. Wedage et al. [63] used terahertz technology to sense climate change in order to protect crop growth. Moreover, the terahertz spectrum is used for atmospheric sensing for weather prediction. Jiang et al. [64] investigated a technique based on terahertz radiation for grain storage quality detection, which significantly reduces the damage of stored grain due to its characteristics of low energy, high permeability, and the high signal-to-noise ratio of terahertz radiation.

Due to the favorable characteristics of the terahertz band mentioned above, we believe that terahertz-related technologies will have more agricultural applications in the future. In the following, we list some potential applications.

(1) Pest detection: Terahertz waves, which typically have a wavelength of a few picometres, are very suitable for wireless sensing because of their high penetration capacity and low energy consumption. Terahertz waves can be used to detect plant pests and thus prevent plant diseases.
(2) Food safety detection: Terahertz spectroscopy has the potential to identify weak intermolecular interactions. It can be used to detect heavy metal substances that are generally contained in pesticides. Therefore, it is very appropriate to use terahertz waves to detect pesticide residues, as well as heavy metals, in food.
(3) Water quality monitoring: Substances dissolved in water show unique physical characteristics. When radiated in a terahertz field, special spectral imprints may be observed. Thus, terahertz waves can be used to detect water contamination.

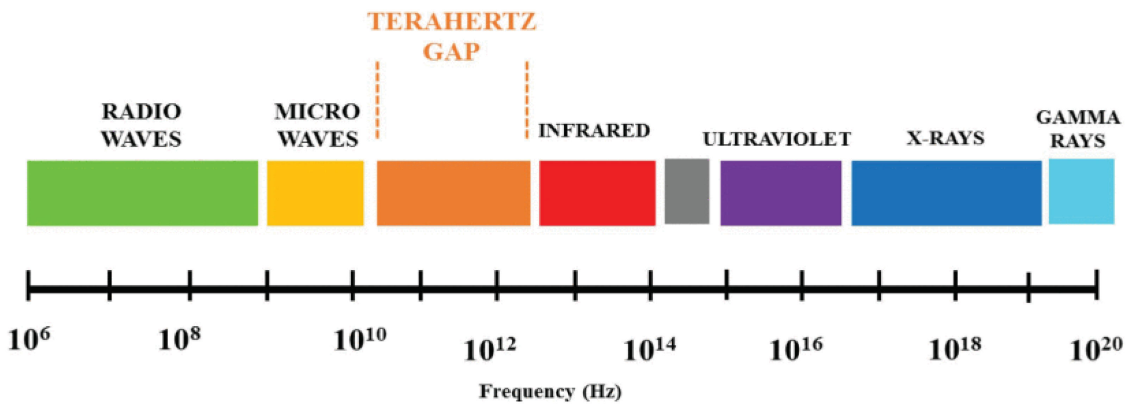

Figure 3. Terahertz gap in the electromagnetic spectrum [65].

3.3. Reconfigurable Intelligent Surface (RIS)

The RIS is an artificial electromagnetic surface structure with programmable properties, which was developed from metamaterial technology [66]. Thanks to its advantages of low cost, low power consumption, programmability, and ease of deployment, the RIS has become an important research direction for future 6G wireless networks (see Figure 4). An RIS is designed as a spatial electromagnetic wave modulator that can intelligently reconfigure the wireless propagation environment in a communication system [67]. The RIS is beginning to play an essential role in many more aspects of wireless communications with its continuous development [68–71]. The use of an RIS can have a significant impact on the terahertz radio system, and not only impact micro-wave communications. It is well known that the very high propagation attenuation and molecular absorption of terahertz frequencies results in a limited transmission distance and coverage. Benefiting from an RIS, the coverage of a terahertz communication system can be greatly improved [72]. Therefore, the agricultural application of terahertz technology can considerably benefit from introducing an RIS.

Based on the powerful ability to reconfigure wireless channels, several studies have explored the application of an RIS to agriculture. Zhang et al. [73] exploited an RIS for backscatter communication in an agricultural sensor network, which can reduce agricultural sensors' cost and power consumption, as well as increase their monitoring range. Liu et al. [74] proposed to use solar harvesting and RIS techniques for sensing in agriculture, wherein a RIS can improve the wireless energy transfer efficiency and enlarge the coverage area. The proposed design successfully addresses the issue of poor sustainability in agricultural sensing activities.

The RIS is a rapidly evolving technology, and the corresponding standardization and industrialization have begun. It is believed that agriculture will also benefit from the powerful capabilities of the RIS. In the following, we list some potential applications.

(1) Communications in remote areas: It is not cost-effective to densely deploy communications infrastructure such as base stations in remote rural areas. Instead, an RIS can improve the coverage and quality of service of communication systems by adjusting the propagation environment, with a low cost for deployment and maintenance. Therefore, an RIS is very suitable for aiding communication in rural areas.
(2) Agricultural precision sensing: An RIS can increase the number of communication links, thus improving the accuracy of wireless sensing, with low cost and easy deployment. Therefore, an RIS is very suitable for precise agricultural sensing activities.

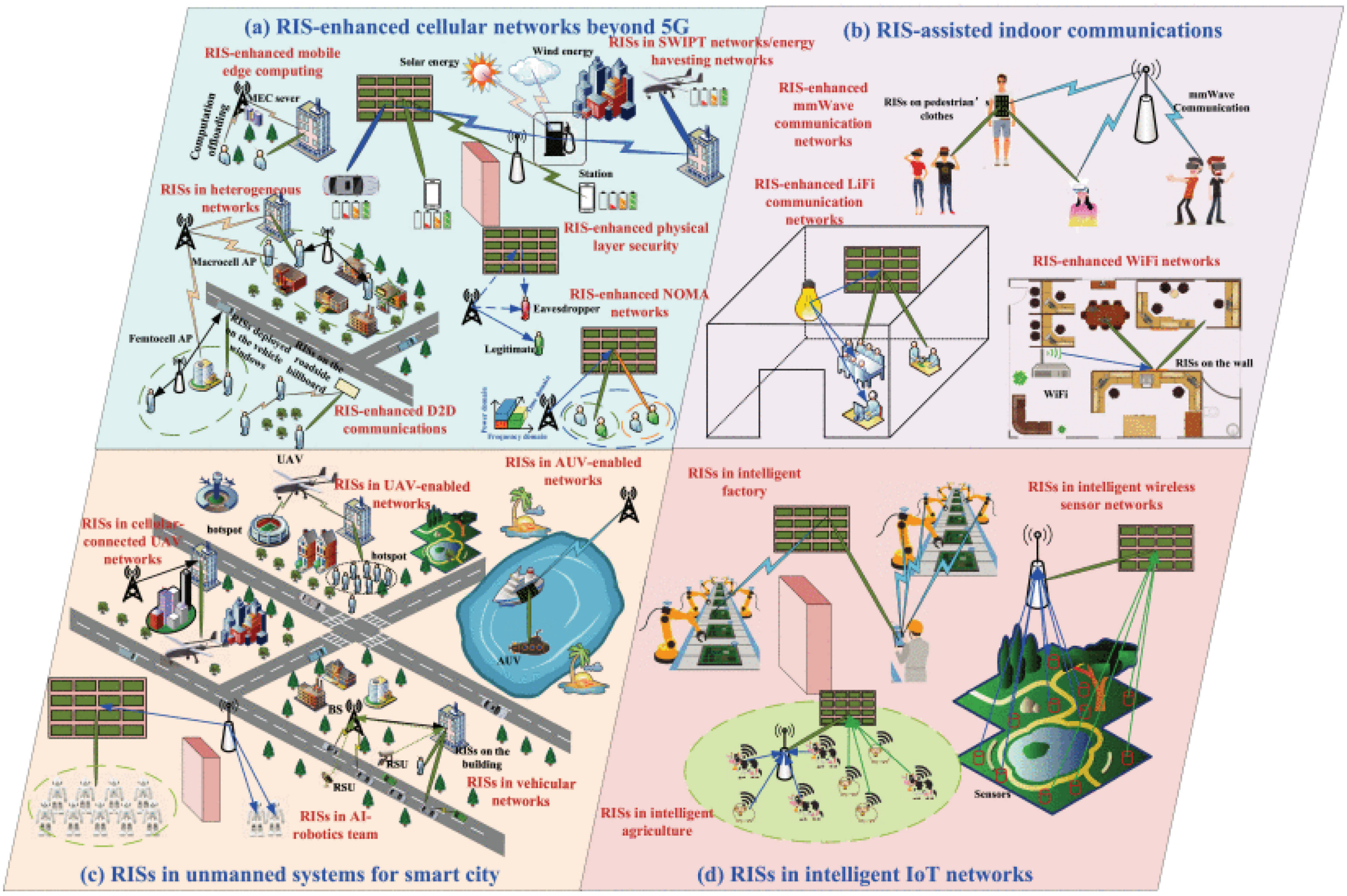

Figure 4. The RIS in wireless communication networks [75].

3.4. Wireless AI

AI (Artificial Intelligence) is a subfield of computer science. AI attempts to understand the nature of human intelligence in order to act as a human would in performing various tasks [76]. The main research areas of AI currently include image processing, natural language processing, and intelligent robotics. Meanwhile, the application areas of AI are also expanding rapidly. Specifically, wireless AI (or AI-empowered wireless technology), which is the combination of AI and wireless communications, has become an important research direction in 6G. AI has shown important application potential in various aspects of wireless communications, such as modeling, learning and predicting complex unknown wireless propagation environments, signal processing, network state tracking, intelligent scheduling, and network deployment optimization (see Figure 5). Moreover, AI is expected to contribute to the evolution of future communication models and changes in network architectures [77]. AI-enabled physical layer technologies for 6G mobile communications include wireless environment modeling and sensing [78], channel estimation/prediction/feedback [79], end-to-end design [80], channel compilation codes [81], modulation and waveform techniques [82], source channel co-coding [83], OFDM receiver design [84], multi-antenna transceivers [85], multi-user access [86], active user detection [87], and localization [88]. There are also many emerging AI-empowered link layer technologies for 6G mobile communications, such as power allocation [89], channel allocation [90], access control [91], link scheduling [92], and wireless resource scheduling based on a smart agent [93]. Other works in wireless AI are AI-based wireless network architecture [94], AI-based transport-layer congestion control [95], AI-based service rate control [96], AI-based demand prediction and caching techniques [97], and AI-based wireless distributed computing [98].

AI has fruitful applications in agriculture, such as plant disease detection [99], agricultural machinery health monitoring [100], and digital soil mapping [101]. Idoje et al. reported the latest research progress on the application of AI in agriculture in [102], which is very helpful for our understanding of AI-enabled smart farming. As for applications concerning the combination of wireless communications and AI in agriculture, most of the existing literature introduces AI into wireless sensor networks for intelligent sensing and monitoring. Vijayakumar et al. [103] designed an automated irrigation system. The system uses a wireless sensor network to collect the farmland's environmental parameters (humidity, moisture, etc.). An artificial neural network is adopted to analyze the collected parameters to determine when it is appropriate for irrigation. The proposed system can save 92% water compared with the traditional irrigation systems. Vincent et al. [104] designed a sensor network to monitor soil parameters, which can also analyze soil conditions using AI. The system can help farmers determine whether the land is suitable for further cultivation, which helps in reasonable farmland use. Dasgupta et al. [105] proposed an AI-based agricultural expert system. The system can collect agricultural data such as annual precipitation, soil pH, etc. and utilize deep learning to intelligently recommend suitable crop precipitation to farmers. Somov et al. [106] developed an IoT-based monitoring system. The system can monitor greenhouse environmental parameters via a wireless sensor network and make appropriate adjustments to keep the crop-growing environment in its optimal state. Furthermore, neural networks are used to predict whether the current greenhouse environment will cause crop diseases, thus enabling early prevention.

Although there is no research directly related to wireless AI in agriculture, it is believed that it can undoubtedly contribute to agricultural development. In the following, we list some potential applications.

(1) Resource allocation optimization: AI-based scheduling of wireless resources is crucial to developing low-power and green agriculture. Using AI to allocate wireless resources will lead to more efficient resource usage, thus improving the efficiency of wireless agricultural sensors and reducing power consumption.

(2) Optimization of wireless network architecture: In the future, by introducing Artificial Intelligence, networks will learn to make autonomous decisions and evolve according

to application scenarios and requirements. The network architecture will also be more flexible in its deployment, thus increasing the efficiency of the network and achieving energy savings, load balancing, and coverage optimization. Such a network will improve the level of agricultural cultivation and production systems and drive agricultural activities to be intelligent and green.

(3) AI-based wireless sensing: In agricultural fields or greenhouses, it is difficult to find out the detailed distribution of crops by image recognition due to the dense foliage of crops or other factors. In contrast, wireless sensing is not seriously affected by these factors and is therefore more suitable for locating crops. The combination of AI and wireless positioning can effectively improve positioning accuracy.

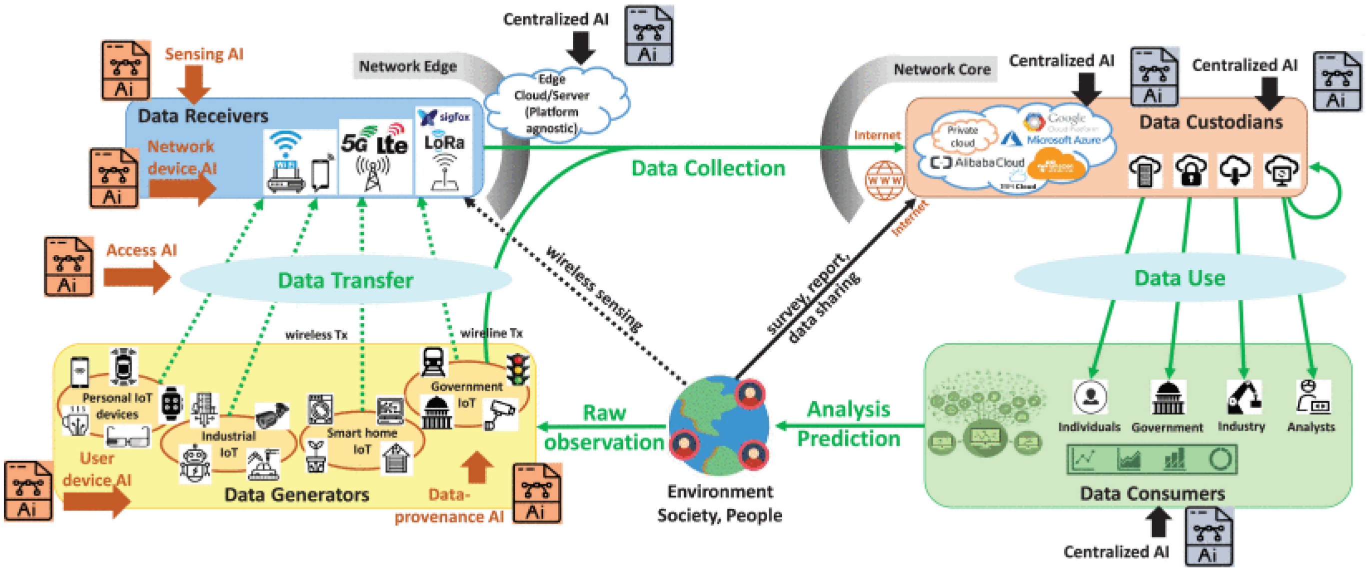

Figure 5. An illustration of the wireless AI paradigm [107].

3.5. Integrated Sensing and Communications (ISAC)

ISAC refers to integrating radar and wireless communication systems on the same hardware platform so that both systems can share hardware, software, and radio resources to enable simultaneous sensing and communications. ISAC improves the efficiency of the spectrum, hardware utilization, and information processing [108]. In the future, 6G will be an essential facilitator for many emerging applications (e.g., autonomous driving, furniture control, motion recognition, etc.) that require both high-quality communication and high-precision sensing (see Figure 6). Therefore, integrating sensing and communications has become a consensus in industry and academia [109]. On the other hand, wireless communication systems and radar sensing systems are moving in a similar direction (higher frequency bands, larger antenna arrays, and smaller size), making it possible to integrate sensing and communications. There are two branches of ISAC technology. Specifically, the communications-centric system requires prioritizing the communications function before supporting the sensing function. System performance metrics focus on communication indicators such as spectral efficiency, channel capacity, signal-to-noise ratio, and bit error rate. Sensing-centric systems require that the communications function does not deteriorate the sensing function. System performance measures are focusing on target parameter estimation accuracy, detection, and recognition probability. Currently, research on ISAC has reached a stage where they are integrated. In this stage, communications and sensing will achieve a comprehensive and multi-level deep integration of spectrum resources, hardware devices, waveform design, signal processing, protocol interfaces, network collaboration, multi-point sensing, etc. Communications and sensing will achieve a win-win situation, and their capabilities will be significantly enhanced.

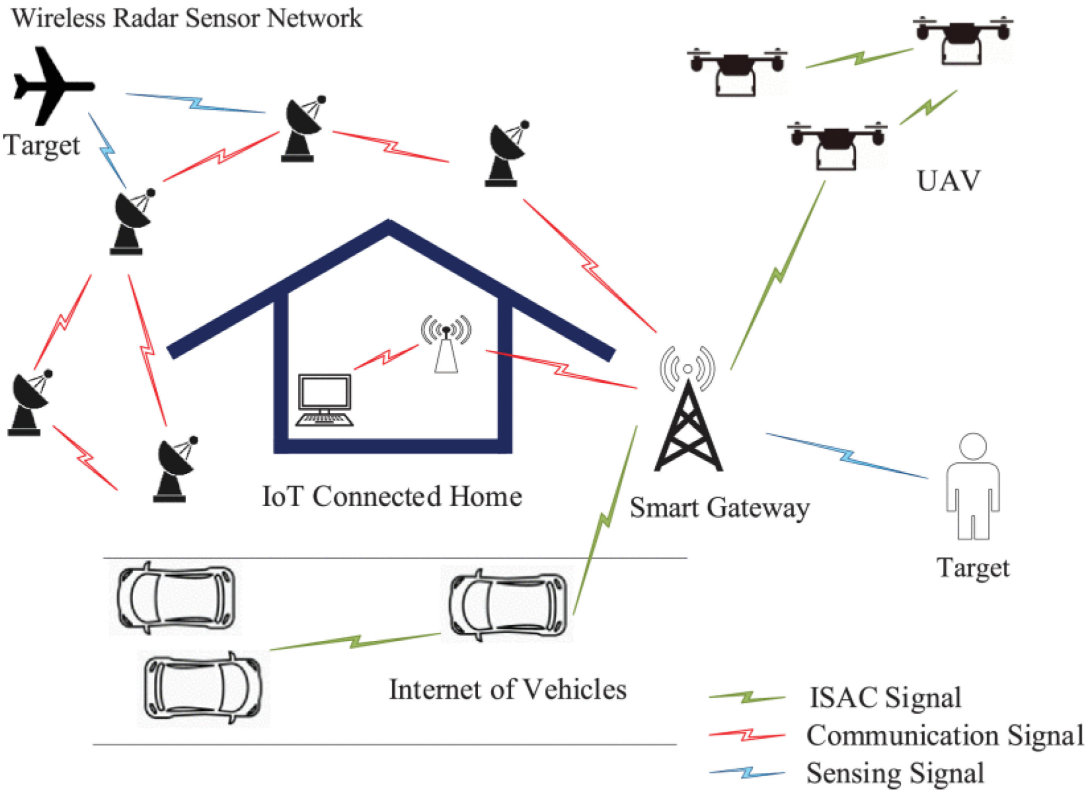

Figure 6. An illustration of the applications of ISAC [110].

Following our investigation, we found no applications for ISAC in agriculture. However, it does not mean that ISAC is useless for agriculture, and ISAC has many advantages which are favorable in agricultural activities, such as cost savings, reduced device size, reduced power consumption, improved spectrum efficiency, and reduced interference between communications and sensing systems. There are also many scenarios in which agricultural activities simultaneously require communications and sensing, and so we believe ISAC has a lot to offer in agriculture. Here are some potential application examples:

(1) The application of millimeter wave technology to ISAC systems improves the communication and sensing capabilities of the system, thus increasing its potential for usage in agriculture. A good example is the prevention of plant diseases, where cameras may not be able to capture pests in greenhouses or farm fields due to the shading of crop leaves. Non-optical imaging technologies, such as millimeter wave imaging, have a high penetration capacity and can penetrate foliage to detect pests and thus prevent crop infestations early. Another example is in dairy farming. Currently, millimeter wave technology can be used to monitor animal behavior with high accuracy, and it has the advantage of non-visual distance. Meanwhile, the communications function of millimeter wave-based ISAC systems can support the transfer of the monitoring data such as alert messages for abnormal animal behavior and images/videos of the pests.

(2) ISAC with space–air–ground-integrated networks can be far more effective in some agricultural applications than those solely based on terrestrial networks. Forest protection is one typical application. Forests are generally large-scale and located in rural areas. Space–air–ground-integrated networks are an efficient approach to provide communications service. Moreover, plants always shade each other. Hence, it would be costly and of high energy consumption to solely rely on cameras for monitoring. Sensing with space–air–ground-integrated networks allows for the comprehensive monitoring and early spotting of forest anomalies.

3.6. Massive MIMO

By deploying super-sized antenna arrays using new materials, a massive MIMO can achieve larger spectral and energy efficiency, as well as larger and more flexible network coverage compared with a traditional MIMO system (see Figure 7). Saleem et al. in [111,112] provide an update on the latest research progress in massive MIMO, which is useful for exploring how state-of-the-art massive MIMO technology can be used in agriculture.

Antenna technology is critical to realize the theoretical gain of MIMO systems. Kulkarni et al. [113] investigated a flexible four-port, four-element interconnected MIMO antenna that can be used for 5G and an X-band of below 6 GHz. Flexible antennas in 5G were explored in-depth in [114]. Kulkarni et al. [115] designed a four-port DGS MIMO antenna with very high gain for use in wireless industrial applications. As a predecessor technology to massive MIMO, MIMO has been used in various agricultural applications, for example, underground sensing for smart irrigation using MIMO [116] and crop growth detection by increasing the resolution of agricultural sensors using MIMO [117]. Massive MIMO channels exhibit some unique characteristics, including the channel hardening phenomenon, elevation characteristics, the spherical wave-front assumption, and spatial non-stationarity. The channel hardening phenomenon indicates the asymptotic mutual orthogonality among the channels between the users and the base station, which can considerably benefit the signal processing. Elevation characteristics describe the elevation dispersion caused by the method of antenna installation, i.e., the antennas are usually installed in more than one plane. The spherical wavefront assumption is due to the fact that when being served by a large antenna array, it becomes more likely that the location of the users is within the Rayleigh distance, wherein the near-field effect appears. Spatial non-stationarity means that the wide-sense stationary assumption for the channel model is no longer appropriate since the channel corresponding to the different antennas on a large array may experience different clusters. In the current studies for massive MIMO in smart agriculture, the considered scenarios are generally open terrain [118], and the channel still exhibits the aforementioned characteristics. These characteristics should be carefully taken into consideration when designing a massive MIMO system in agriculture, especially for signal processing, beamforming design, and network planning. There are a few works investigating the application of massive MIMO in agriculture. Bana et al. [119] innovatively utilized a massive MIMO for agricultural IoT. A massive MIMO can support large-scale communications with ultra-low latency and can be used for large-scale and complex agricultural activities such as precision sowing on large farms. Zhao et al. [120] used a massive MIMO to assist UAV and satellite networks, which improves the performance of integrated air–space–ground communication networks. It allows the space–air–ground-integrated communication network to better serve the agricultural activities.

A massive MIMO carries more antennas than a conventional MIMO, which can achieve a much higher array gain, channel capacity, and spectral efficiency. It is highly sensitive to changes in channel state, thus enabling it to provide powerful support for agricultural activities that require high-precision sensing, such as earthquake prediction and accurate harvesting on large farms. In addition, a massive MIMO can provide high quality, wide coverage communication services to support multimedia communications and wireless sensor networks in agricultural activities.

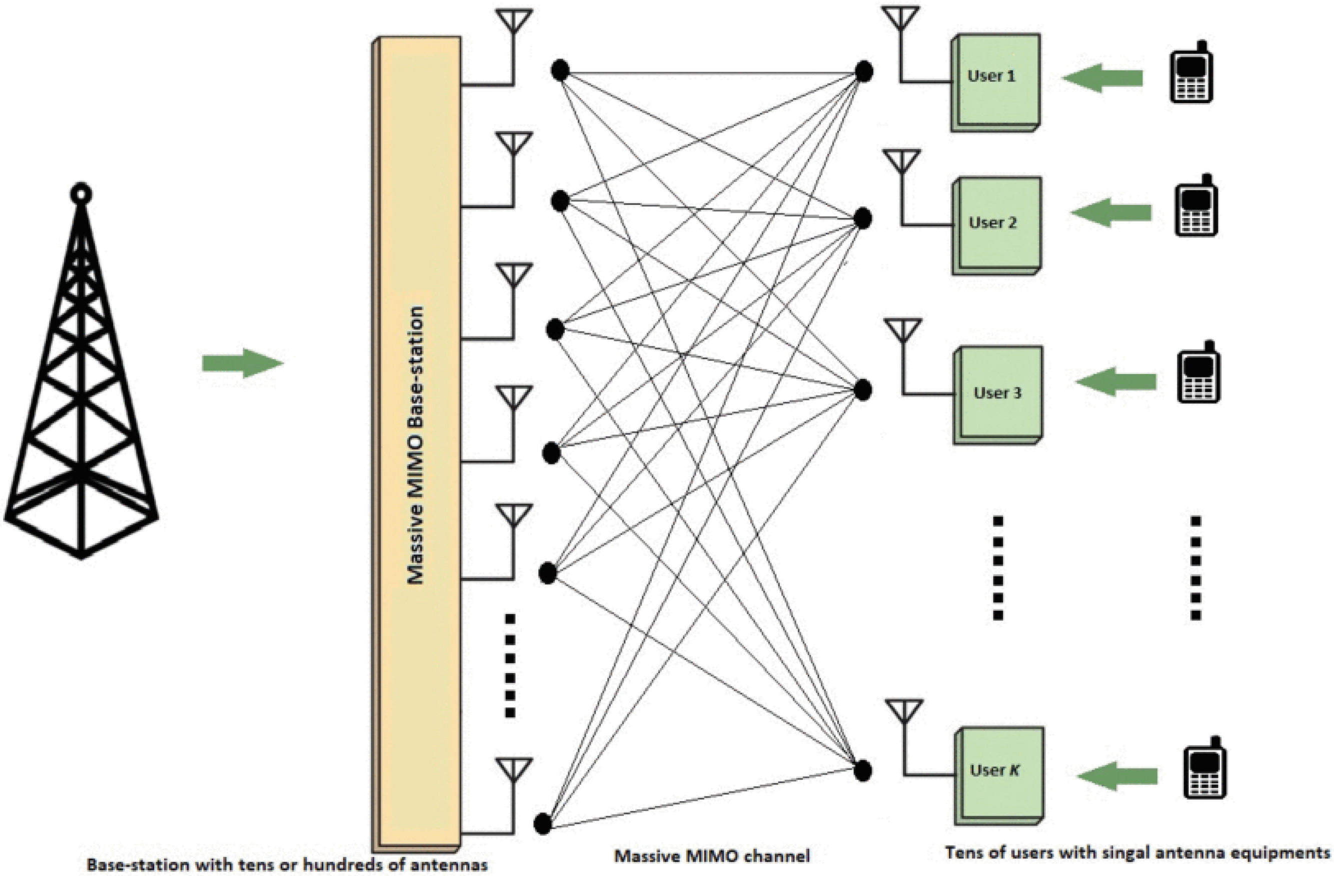

Figure 7. Massive MIMO architecture [121].

3.7. Digital Twins

Digital twin technology can map or clone a physical entity onto a virtual digital space based on various means and techniques [122]. In general, a digital twin system should consist of a physically existing object, its digital clone, and the information data between them, which can be utilized to enhance the performance of objects in the physical space [123]. The digital twin is one of the fastest growing and most important technological advancements. With the development of Artificial Intelligence and big data, digital twin technology is gaining more and more attention. It is widely recognized as having great potential for applications in manufacturing, aerospace, healthcare, and medicine [124] (see Figure 8).

Due to the powerful ability of digital twins to mapping physical devices in virtual space, many researchers have introduced digital twins into agriculture. Ghandar et al. [125] designed a low-cost, high-precision digital twin framework for farmland, consisting of an agricultural wireless sensor network and a cloud server. Its most significant advantage is the near real-time remote monitoring of farm conditions instead of manual monitoring, which makes the proposed system suitable for the deployment on large-scale farms. Batty et al. [126] proposed an approach using deep learning and digital twin technology to enable aquaponics, i.e., the symbiosis of fish and plants. The designed framework can significantly save resources such as water, soil, and lighting. Howard et al. [127] constructed a new model combining digital twins, big data, and IoT technologies for greenhouse agriculture. The model can predict the future state of a greenhouse according to the input data of its present and past states, which can considerably help maintain a suitable greenhouse environment. Jans-Singh et al. [128] designed an underground farm based on digital twin technology. The designed system can automatically set the optimal environment for crop growth while achieving low electrical energy consumption. In addition to the aforementioned cases, we believe that digital twin technology will be applied in more aspects of agriculture in the future.

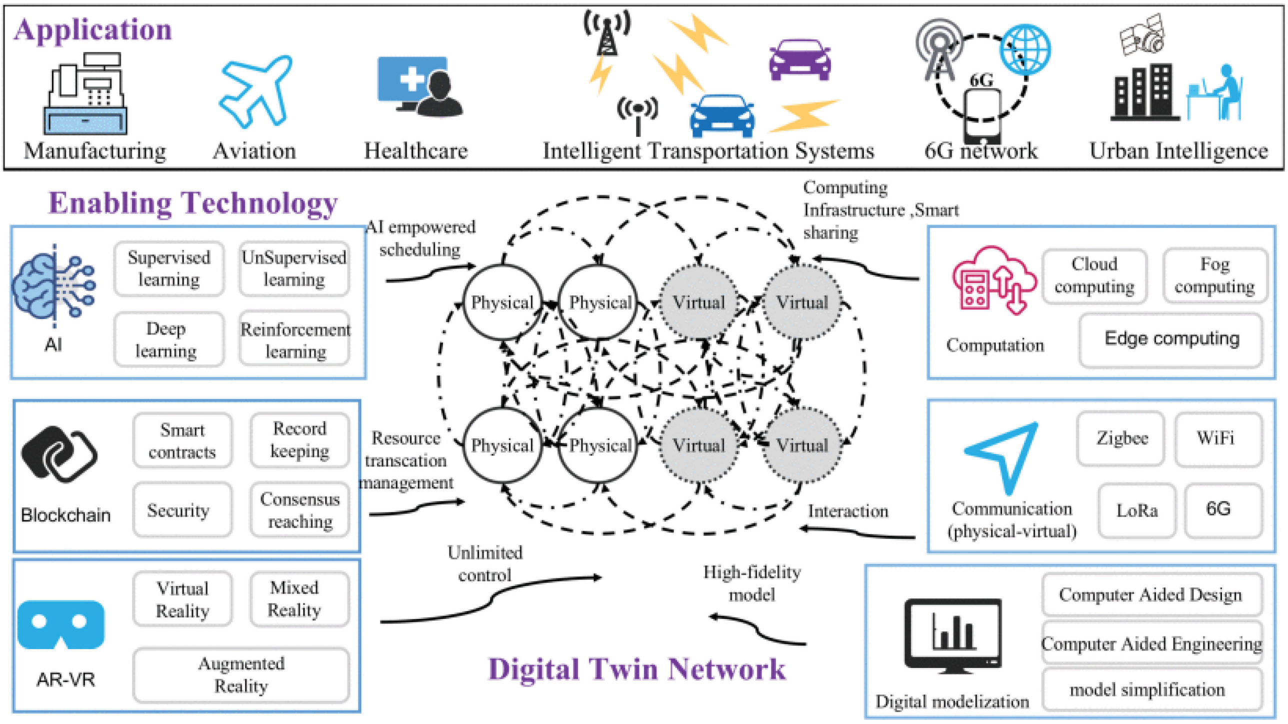

Figure 8. Applications of digital twin networks [129].

3.8. Ambient Backscatter Communications

As early as 1948, Harry Stockman proposed an asymmetric communication architecture for transceiver modules, namely, ambient backscatter communications. The basic principle is that a backscatter device modulates, reflects, and receives signals from an RF signal source to send data, rather than generating an RF signal by itself (see Figure 9). Backscatter communication technology has been studied for a long time and is now very mature and widely used in RFID (radio frequency identification) systems [130]. Moreover, ambient backscatter communications provide an effective solution for the communication of large numbers of low-power nodes in a passive IoT. The IMT-2030 (6G) Promotion Group points out that backscatter communication is one of the key technologies for building a green, energy-efficient, low-cost, and flexibly deployable future Internet of Things (IoT), and it is an important means of realizing the "smart connection of everything".

Due to the advantages of backscatter communication discussed above, it has a very wide range of applications in agriculture. In [131], Daskalaki et al. proposed a novel sensor node/tag that monitors plants' water pressure using backscatter communication from an ambient frequency modulated signal (an FM music signal). The introduction of backscatter communication is of high importance for smart farming, allowing it to replace traditional ground-based soil moisture sensing. Daskalakis et al. [132] designed a new wireless temperature sensor that can be used to measure the temperature of crops in real-time. The sensor communication takes advantage of a backscattered radio technique by efficiently utilizing the ambient FM station signals, which is FM0-encoded and amplitude modulated. Yang et al., in [133], investigated novel UAV-assisted backscatter communication where a UAV first collects data from multiple ground-based backscatter tags via time-division multiple access (TDMA), and then flies into the coverage area of a ground base station and uploads its collected data. This system can well satisfy the demands of agricultural IoT for energy-efficient communications.

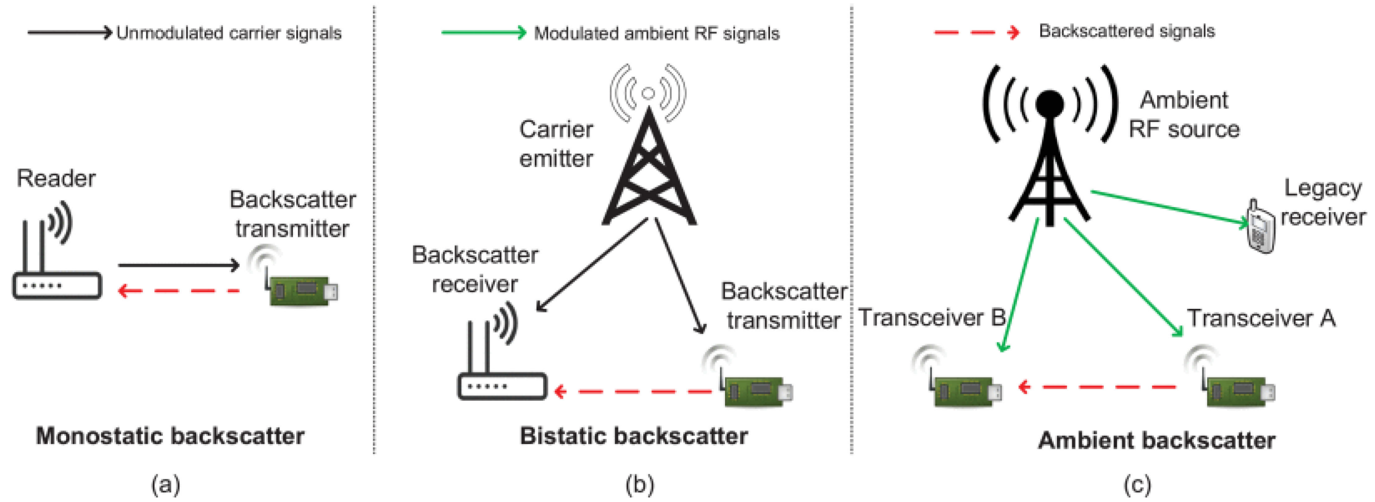

Figure 9. Paradigms for backscatter communications [134]. (**a**) Monostatic backscatter; (**b**) Bistatic backscatter; (**c**) Ambient backscatter.

4. Conclusions

In this article, firstly, we briefly introduced the concept of smart agriculture and its essential role in human society. We have also reviewed the evolution of agriculture, which can be summarized by four stages. Then, we introduced several mature wireless communication technologies and showed that these technologies have been considerably contributing to agricultural activities. However, these technologies have their own shortcomings, and their applications in agriculture are considerably limited. Hence, it is essential to explore the application of more advanced wireless communication technologies in agriculture, i.e., the emerging 6G technologies. We have briefly introduced the concept of 6G and detailed descriptions of several key 6G technologies. More importantly, we have explored the features of these 6G technologies from the perspective of agriculture and their existing, as well as potential, applications in smart agriculture.

Sixth-generation technology is naturally a wide-ranging concept. There is a plethora of 6G technologies that have recently emerged, and not all of them are discussed in detail in this review, such as distributed networking technologies [135], secure endogeneity [136], arithmetic networking technologies [137], programmable networking technologies [138], trusted data services [139], immersive multisensory networks [140], and semantic communication [141]. We believe that more 6G technologies will be exploited in agricultural applications in future research, which will enable agriculture to be highly automated and intelligent.

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Abbreviations

SAGIN	Space–air–ground-integrated networks
RIS	Reconfigurable intelligent surfaces
AI	Artificial Intelligence
ISAC	Integrated sensing and communication
MIMO	Multiple-input multiple-output
UAV	Unmanned aerial vehicle
IoT	Internet of Things
Wi-Fi	Wireless fidelity
DT	Digital twins

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