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Edge Computing in Agriculture

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ABSTRACT

Agriculture is the cornerstone of human survival, yet it faces unprecedented pressures. Edge computing represents a paradigm shift in agriculture, addressing the fundamental limitations of cloud-centric architectures in rural environments. By decentralizing computing power and relocating data processing to the “edge” of the network-physically closer to the data sources such as tractors, soil sensors, and greenhouses-edge computing fundamentally restructures the agricultural data paradigm. Edge computers process sensor data from tractors, drones, and planters instantly, enabling precise, real-time adjustments to planting depth or seeding application. In agriculture, this means that sensor data can be processed locally, on the farm itself. This kind of real-time processing enables farmers to react quickly when something changes. This paper explores the role of edge computing in agriculture.

KEYWORDS: *edge computing, cloud computing, agriculture, smart agriculture, precision agriculture, farming.*

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INTRODUCTION

As the global population continues to expand and climate change intensifies, the agricultural sector faces unprecedented pressure to maximize productivity while ensuring sustainable resource utilization. While cloud computing has provided the foundational infrastructure for data-driven agriculture, its reliance on centralized processing introduces challenges related to latency, bandwidth constraints, and connectivity issues in remote rural areas. Edge computing has emerged as a transformative solution to these limitations, enabling localized data processing and real-time decision-making directly on the farm.

It refers to the practice of processing data closer to its source. It is a distributed computing paradigm that brings computation and data storage closer to the location where it is needed. Rather than sending all data to a distant cloud server, edge devices process information locally. Figure 1 shows the symbol of edge computing [1].

The proliferation of connected devices has generated an exponential surge in agricultural data, exposing the limitations of traditional cloud computing frameworks. In conventional cloud-based systems, data must be transmitted to centralized remote servers for processing and analysis. In rural agricultural settings, this approach encounters critical bottlenecks: high communication latency, limited bandwidth, intermittent network connectivity, and the stringent real-time decision-making requirements of dynamic farm operations. Edge computing has emerged as a revolutionary solution to these constraints. From autonomous tractors navigating complex terrain to precision irrigation systems optimizing water use, edge computing is a critical enabler of the digital transformation needed to ensure global food security and sustainable farming practices in the 21st century [2].

CONCEPT OF EDGE COMPUTING

The history of edge computing traces back to the introduction of content delivery networks in the 1990s. The concept was straightforward: place servers close to end-user locations for faster cached image and video transmission. Edge computing was created jointly by Microsoft and their academic collaborators. Today, more and more services are pushed from the cloud to the edge of the network. Since data is increasingly being produced at the edge of the network, it would be efficient to process the data there. Keeping this data closer to its users (at the edge) eliminates many of the problems inherent with the public cloud model. Figure 2 shows how edge computing works [3]. Edge computing allows data from IoT devices to be analyzed at the edge before being sent to the cloud.

Edge computing (EC) or edge cloud is a computing paradigm where substantial compute and storage resources are placed at the edge of the Internet, in close physical proximity to mobile devices, sensors, end users, and IoT devices. It refers to bringing the flexibility and openness of cloud-native infrastructure to that local infrastructure. The idea of "edge" is to do processing near the data source. The terms "cloudlets," "micro data centers," and "fog" are used to refer to these small, edge-located computing nodes or data centers. A *cloudlet* is a cluster of computers well connected to the Internet and can be treated as "data center in a box." The main objective of a cloudlet is to extend the remote datacenter cloud services in close proximity to the end users. Physical proximity is the essence of edge computing since it improves latency, bandwidth, trust, and survivability. While the cloud has revolutionized the way we deal with data, the next wave of that revolution will happen at the edge [4].

A standard edge computing framework consists of three distinct levels [5]:

- The cloud: Which manages the overall data storage and processing.
- The edge: Tasked with near-instantaneous data handling.
- The device: Responsible for initial detection and basic data processing.

These three levels are related in the edge computing architecture shown in Figure 3 [6].

Edge computing covers a wide range of technologies such as wireless sensor networks, distributed data storage, and augmented reality. This has made its way to becoming the core of the data center. The term "edge" refers to the computing devices that sit closer to the sources of data, where the digital world meets the real world. These edge devices typically reside away from the centralized computing available in the cloud and are being created with increasingly compute capabilities. Typical edge devices are smartphones, tablets, sensors, wearables, routers, switches, integrated access devices, multiplexers, smart TV, modern cars, and a variety of MAN/WAN access devices. Edge computing enables analytics and data gathering to occur at the source of the data.

Edge computing covers a spectrum of technologies such as cloudlets, fog computing, and mobile edge computing. A combination of edge and cloud computing is referred to as *fog computing* because it combines centralized and distributed computing resources into a single architecture. (Edge computing is a relatively new concept that should not be confused with fog computing.) It is practically unsafe and unnecessary to send such a large amount of data to the cloud. A comparison between cloud computing, edge computing is illustrated in Figure 4 [7]. Compared to cloud computing, fog computing and edge computing have the following five advantages [8]: (1) greater data transmission speed, (2) less dependence on limited bandwidths, (3) greater privacy and security, (4) greater control over data generated in foreign countries where laws may limit use or permit unwanted governmental access, and (5) lower costs because more sensor-derived data are used locally, and less data are transmitted remotely. Figure 5 shows edge computing [9], while Figure 6 shows how edge data is processed [3].

EDGE COMPUTING IN AGRICULTURE

Agriculture, as one of the world's oldest and most critical industries, has always been at the forefront of innovation to meet the growing demand for food, fiber, and fuel. The global agricultural sector is at a critical juncture. The industry faces the daunting challenges of climate change, resource depletion, the necessity to minimize environmental impacts, and the need to meet the food demands of a growing global population while managing limited natural resources. In response, "smart agriculture" or "precision agriculture" has evolved, leveraging information and communication technologies (ICTs) to optimize agricultural processes. Central to smart agriculture is the deployment of IoT devices, drones, and autonomous machinery, which continuously collect vast amounts of environmental and operational data. Traditional cloud computing architectures struggle to manage this data influx due to inherent limitations in latency, bandwidth, and connectivity in rural environments. Edge computing addresses these bottlenecks by processing data locally-on tractors, in greenhouses, or via field sensors-enabling real-time autonomous control, instant predictive analytics, and localized decision-making. It emerges as a tractable and transformative solution by decentralizing computational resources and relocating data processing to the network's periphery-closer to the data source [2]. Figure 7 shows a representation of edge computing in agriculture [10], while Figure 8 shows a farmer [11].

APPLICATIONS OF EDGE COMPUTING IN AGRICULTURE

The deployment of edge computing enables a wide array of precision agriculture applications that require immediate responsiveness and robust operation in connectivity-constrained environments. Its applications in precision agriculture, autonomous machinery, livestock monitoring, and supply chain traceability are not only increasing yields and operational efficiency but also driving the sector toward greater sustainability. Common applications of edge computing in agriculture include the following [2,11]:

- *Smart Agriculture:* The agricultural sector must navigate the dual challenges of climate change and environmental degradation, which threaten arable land and water resources.

  To address these compounding issues, the concept of "smart agriculture" (or precision agriculture or agriculture 4.0) has gained prominence. Smart agriculture is rapidly evolving in response to growing global demands for food security and sustainable resource management. It leverages the Internet of things (IoT), artificial intelligence (AI), big data analytics, and advanced robotics to optimize farming practices, minimize resource waste, and maximize yields. Historically, cloud computing has been the primary engine driving smart agriculture, offering scalable storage and powerful analytical capabilities. However, the agricultural environment is inherently distributed and often lacks reliable internet infrastructure. The transmission of massive datasets from remote farms to centralized cloud servers introduces significant latency, consumes high bandwidth, and poses security risks. In smart agriculture, edge computing does not replace the cloud; rather, it operates within a collaborative "cloud-edge-device" architecture. Unmanned aerial vehicle (UAV) platforms have become deeply aligned with the core themes of precision agriculture due to their high mobility and flexibility, effectively addressing challenges such as dynamic canopy structural variations and environmental heterogeneity. Collaborative operations between UAVs and agricultural machinery via end–edge–cloud architecture are becoming foundational to smart agriculture. Figure 9 shows smart agriculture [12], while Figure 10 depicts the applications of UAVs in precision or smart agriculture [13].

- *Autonomous Farm Vehicles*: As the global digital transformation of agriculture accelerates, the widespread deployment of farming equipment has triggered an exponential surge in agricultural production data. The integration of edge computing with real-time data processing is revolutionizing agricultural machinery. Autonomous tractors, harvesters, and drones represent a significant leap in agricultural efficiency. These vehicles generate immense volumes of data through LiDAR, GPS, and high-resolution cameras. Relying on cloud connectivity for navigation and obstacle avoidance is impractical due to latency and the risk of network dropouts. Edge computing allows these vehicles to process spatial data locally, enabling real-time path planning, variable rate application of inputs (fertilizers and pesticides), and immediate responses to dynamic field conditions. Figure 11 shows a self-driving vehicle [11].

- *Autonomous Farming*: The shift from smart farming to autonomous farming is heavily reliant on edge computing. Autonomous tractors and harvesters must make millisecond-level decisions to navigate complex terrain, avoid obstacles, and adjust operational parameters (e.g. seeding depth or threshing drum speed). Relying on cloud connectivity for these safety-critical and operation-critical functions is unfeasible. Edge AI enables these machines to process LiDAR, radar, and visual data locally, ensuring continuous, safe operation even in complete network isolation. Just like agribots, a greenhouse or even entire farms can be put on autopilot using IoT edge computing. This means the closed ecosystem can take care of itself without relying on a remote server to process the collected data and make decisions about routine processes, e.g. watering the plants, feeding the cattle, managing the temperature, light, humidity in the room, etc.

- *Disease Detection:* Early detection of pests, diseases, and nutrient deficiencies is critical for minimizing crop loss. Edge AI-the deployment of machine learning models on edge devices-facilitates on-site image analysis. For example, a drone equipped with edge computing capabilities can scan a field, identify signs of blight using a lightweight convolutional neural network (CNN), and instantly transmit the specific location to the farmer or trigger a targeted pesticide application. This localized processing drastically reduces the need to transmit large image files over limited rural networks.

- *Precision Crop Management*: Edge computing enables highly localized and precise crop management. In field settings, sensor networks monitor soil moisture, temperature, and nutrient content. Edge-powered variable rate technology allows farmers to apply water and fertilizer only when and where needed, optimizing resource usage and boosting yields. In controlled environments like greenhouses, edge computers maintain optimal growth conditions. Sensors continuously track humidity, temperature, and CO2 levels. Edge server systems automatically adjust these parameters in real-time, ensuring plant health even if the connection to the central cloud is severed.

- *Precision Irrigation*: Water scarcity is a pressing global concern, making efficient irrigation vital. Edge-enabled sensor networks continuously monitor soil moisture, temperature, and humidity. Instead of waiting for cloud-based algorithms to dictate watering schedules, edge controllers can autonomously adjust irrigation systems in real-time based on localized microclimates. This ensures crops receive optimal hydration while significantly reducing water waste. Figure 12 shows an irrigation system [11].
- *Livestock Monitoring*: Edge computing is also transforming livestock farming. It is increasingly utilized in livestock management to enhance animal welfare and farm productivity. In animal husbandry, wearable IoT sensors track the vital signs, movement, and feeding behaviors of livestock. Edge computing processes this biometric data locally, instantly alerting farmers to anomalies that may indicate illness, distress, or changes in reproductive status. Prompt intervention improves animal welfare, prevents the spread of disease, and enhances overall herd productivity.
- *Digital Twins:* The concept of the “digital twin”-a highly detailed, dynamic virtual replica of a physical system-is gaining traction in agriculture. Edge computing is the critical enabler of real-time digital twins. By continuously feeding local sensor data into a virtual model of a specific field or greenhouse, farmers can simulate the outcomes of various interventions (e.g., applying a specific pesticide or altering irrigation) before committing capital and resources in the physical world.

BENEFITS

The integration of edge computing into agricultural systems provides several foundational advantages over traditional cloud-centric models. These benefits are primarily driven by spatial proximity to data generation and localized computational capabilities. The benefits of edge computing in agriculture include real-time data processing, operational efficiency, resource optimization, and its applications in autonomous machinery and supply chain traceability. The recognition of these benefits is driving rapid growth in the agricultural edge computing market. Other benefits of edge computing in agriculture include the following [2,14]:

- *Low-Latency Response*: By establishing a real-time decision-making unit at the source of data collection, edge computing circumvents the multi-hop routing delays associated with remote data transmission. Raw data streams captured by sensors are directly cleaned, features are extracted, and decisions are generated at the edge nodes. This capability is vital for dynamic scenarios, such as autonomous planters adjusting seed spacing or combine harvesters diagnosing threshing drum blockages in real-time.
- *Bandwidth Optimization*: Edge computing substantially decreases the volume of data requiring cloud transmission. Through raw data preprocessing and feature extraction, edge nodes intelligently filter high-value decision features (e.g., crop stress indices) while eliminating redundant raw data. This ensures the stable operation of bandwidth-intensive tasks, such as transmitting high-resolution images from Unmanned Aerial Vehicles (UAVs), even under constrained network conditions.
- *Data Localization:* Many rural operations cannot rely on stable internet connections. Edge computing allows essential systems to function independently, without a constant link to the cloud. Furthermore, processing data locally minimizes the network exposure of sensitive agricultural data, mitigating privacy leakage risks and enhancing overall data security.
- *Enhanced Data Privacy:* The agricultural sector is increasingly recognizing the value of proprietary farming data. Sending sensitive operational data to centralized cloud servers increases the risk of data breaches and cyberattacks. Edge computing inherently enhances security by minimizing the network exposure of raw data. Because data is processed and stored locally on the farm, farmers retain greater control over their intellectual property. Furthermore, edge architectures can implement localized trust domains and secure protocols, significantly reducing vulnerabilities. Keeping sensitive agricultural data on-premises minimizes exposure to cyber threats and data breaches that can occur during transmission to centralized cloud servers. By incorporating encryption algorithms and blockchain technology, edge computing can ensure secure local data storage, protect sensitive information, and

guarantee transmission integrity. This strengthens support for agricultural product traceability and supply chain management.

- *Food Safety*: Beyond the farm gate, edge computing plays a critical role in ensuring food safety and traceability throughout the supply chain. From the moment produce is harvested or livestock is processed, edge sensors can monitor environmental conditions such as temperature and humidity during storage and transit. If a refrigeration unit fails during transport, edge devices can instantly alert operators, preventing spoilage and reducing the risk of foodborne illnesses.
- *Decision-making:* Edge computing plays a central role in transforming precision agriculture by enabling timely, localized, and resource-efficient decision-making. This technology supports more than just fast reactions; it helps farmers make better long-term choices, too. By putting data-driven decision making at the center of everyday work, edge computers play a key role in improving crop yields, managing resource usage, and building toward sustainable agriculture. Using edge computing, agriculture IoT systems can make informed decisions about potential environmental hazards or natural disasters.

CHALLENGES

In spite of its transformative potential, the widespread adoption of edge computing in agriculture faces several systemic challenges. Challenges such cybersecurity, lack of standardization, high initial implementation costs, energy constraints, hardware durability, and interoperability still persist. Other challenges of edge computing in agriculture include the following [2,14]:

- *High Initial Costs:* The transition to edge computing involves substantial upfront investments. Farmers must purchase ruggedized edge hardware, specialized sensors, and local networking infrastructure. For smallholder farmers, particularly in developing regions, these costs are often prohibitive. While the long-term return on investment through increased efficiency and yield is promising, the initial capital expenditure remains a major barrier to widespread adoption.
- *Cybersecurity Threats*: Agricultural edge networks are susceptible to a range of cyber-threats, including data breaches, denial-of-service attacks, and malicious control of automated machinery. A compromised edge node could lead to falsified sensor data, resulting in incorrect irrigation or fertilization, or even the hijacking of autonomous vehicles, posing severe safety risks. The limited computational resources of edge devices often preclude the use of robust, resource-intensive encryption and security protocols, exacerbating these vulnerabilities.
- *Infrastructure Deficits*: While edge computing mitigates the need for continuous cloud connectivity, it still requires a baseline communication infrastructure (such as 5G, LoRaWAN, or Wi-Fi) to link sensors, edge nodes, and the cloud. In many developing nations and remote rural areas, even basic connectivity is lacking, presenting a significant barrier to entry.
- *Energy Efficiency*: Edge devices must operate in harsh agricultural environments, enduring extreme temperatures, dust, and moisture. Furthermore, these devices are often battery-powered or reliant on solar energy. Balancing the computational power required for edge AI with stringent energy constraints remains a significant engineering challenge. As hardware becomes more energy-efficient and AI models become increasingly lightweight, the capabilities of edge devices will expand.
- *Rural Digital Divide*: While edge computing is designed to mitigate the need for constant, high-bandwidth cloud connectivity, it still requires robust local networks and periodic synchronization with central systems. Many agricultural regions, particularly in developing nations and remote areas, suffer from a pronounced "digital divide." Across OECD countries, rural areas consistently lag behind urban centers in mobile download speeds and 5G availability. In fields characterized by complex topography and crop canopies, wireless signal propagation is further degraded, complicating the establishment of reliable local networks necessary for edge nodes to communicate with sensors and machinery.
- *Hardware Durability*: Agricultural environments are inherently hostile to delicate electronic equipment. Edge computing nodes deployed in fields or on machinery must withstand extreme temperatures, high humidity, dust, vibrations, and exposure to agrochemicals. Ensuring the longevity and reliability of edge hardware under these conditions requires specialized ruggedization, which significantly increases manufacturing costs and limits the availability of off-the-shelf solutions.
- *Resource Constraints*: Many edge devices are constrained by limited memory, processing power, and energy supply. Edge devices, by

definition, possess limited processing power, memory, and storage compared to cloud servers. Deploying sophisticated artificial intelligence (AI) and machine learning (ML) models on these resource-constrained devices requires significant optimization. Techniques such as model compression, quantization, and the development of lightweight architectures are necessary to ensure that algorithms can run efficiently at the edge without sacrificing acceptable levels of accuracy.

- *Energy Constraints*: Many edge devices and their associated sensor networks are deployed in remote locations lacking access to stable power grids. Consequently, they rely on batteries or limited renewable energy sources like solar panels. The computational demands of edge AI models-such as real-time image processing for disease detection-can quickly deplete power reserves. Balancing the need for advanced local computation with strict energy efficiency requirements remains a critical bottleneck.
- *Lack of Standardization:* The agricultural technology market is highly fragmented, with numerous vendors offering proprietary sensors, machinery, and software platforms. This lack of standardization creates severe interoperability issues. Integrating diverse edge devices into a cohesive system that can communicate seamlessly with both local sensors and centralized cloud platforms is a complex engineering challenge. Without universally accepted standards for data formats and communication protocols, the scalability and effectiveness of edge computing in agriculture are severely hampered.
- *Skills Gap:* Operating and maintaining sophisticated edge computing systems require specialized technical expertise. Rural agricultural communities often lack the necessary digital literacy and IT support infrastructure. The gap between the complexity of the technology and the technical capacity of the end-users necessitates significant investment in training and user-friendly interface design to ensure successful deployment and utilization.

FUTURE OF EDGE COMPUTING IN AGRICULTURE

Edge computing represents a paradigm shift in agricultural technology, moving the industry away from centralized cloud dependency toward decentralized, localized intelligence. The future of agricultural computing is not a wholesale replacement of the cloud, but rather a synergistic “cloud-edge-device” collaborative framework. This multi-tier architecture optimizes the distribution of computational tasks based on their latency requirements and spatial context. As edge computing in agriculture matures, several advanced technological trends are shaping its future trajectory.

The future of agriculture depends not merely on collecting more data, but on processing it intelligently and acting upon it instantly. Edge computing provides the essential architectural shift required to make this possible. The evolution of intelligent edge architectures, breakthroughs in lightweight artificial intelligence algorithms, the integration of satellite–terrestrial collaborative communication technologies, and innovations in dynamic energy management strategies will collectively propel agricultural edge computing toward higher efficiency, reliability, and sustainability [14].

The future of edge computing in agriculture will likely be shaped by the convergence of several emerging technologies. The rollout of 5G networks will significantly enhance the capabilities of edge systems, providing the high-speed, low-latency connectivity required for advanced robotic automation and swarm intelligence. Furthermore, the development of more sophisticated, lightweight AI algorithms will enable increasingly complex decision-making directly on resource-constrained edge devices. The integration of artificial intelligence (AI) at the edge-often termed Edge AI-is unlocking new capabilities across various agricultural domains. As the global demand for food continues to rise, the widespread adoption of edge computing will be instrumental in securing a productive, efficient, and resilient agricultural future [2].

CONCLUSION

The integration of edge computing into agriculture is not merely an incremental technological upgrade; it is a fundamental restructuring of how agricultural data is utilized. Edge computing represents a critical technological advancement necessary for the realization of sustainable, high-yield smart agriculture. It provides a tractable and highly effective model for realizing the goals of smart agriculture. By enabling low-latency decision-making, reducing bandwidth reliance, and providing offline functionality, it addresses the core limitations of cloud-only architectures in rural environments. It also empowers farmers to optimize resource usage, increase yields, and operate resiliently in the face of environmental and infrastructural challenges.

Ultimately, edge computing is not just a technological upgrade for farming; it is a critical infrastructure requirement for ensuring global food security in an era of unprecedented environmental and demographic challenges. Edge computing is revolutionizing precision agriculture by bringing data processing closer to the field. It is emerging as a core engine driving the transition of smart agriculture toward real-time and intelligent operations. By deploying computing capabilities closer to the network edge, it effectively addresses critical issues such as massive data processing, low-latency response, and energy constraints in agricultural production [14]. More information on edge computing can be found in the book in [15] and the following related journals:

- Agriculture
- Sensors
- Computers and Electronics in Agriculture

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Figure 1 The symbol of edge computing [1].

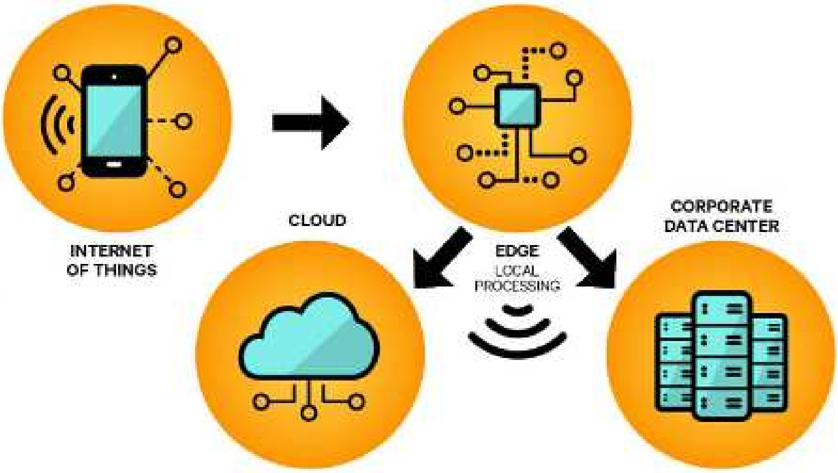

Figure 2 How edge computing works [3].

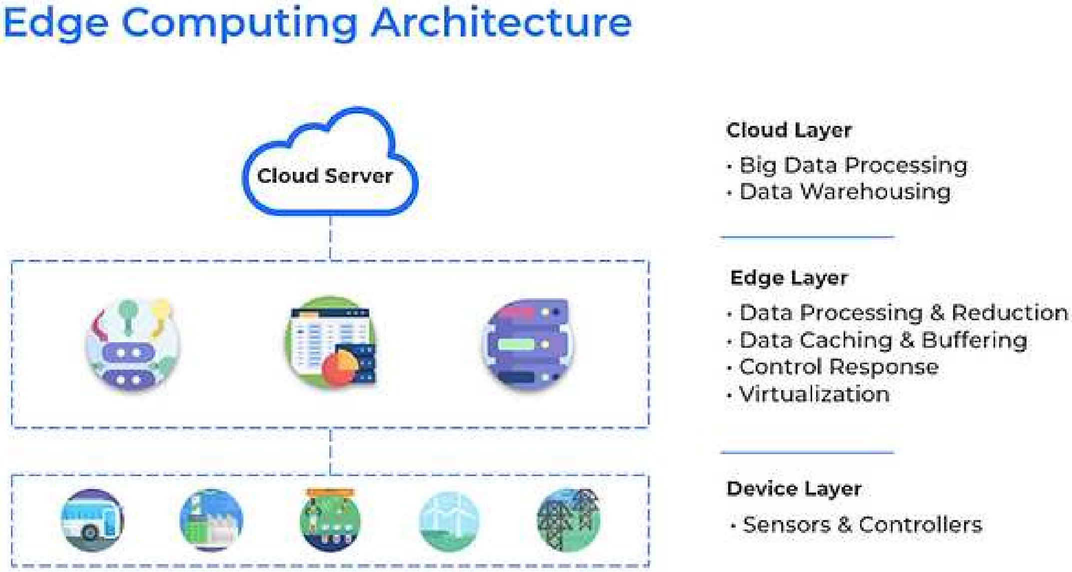

Figure 3 Edge computing architecture [6].

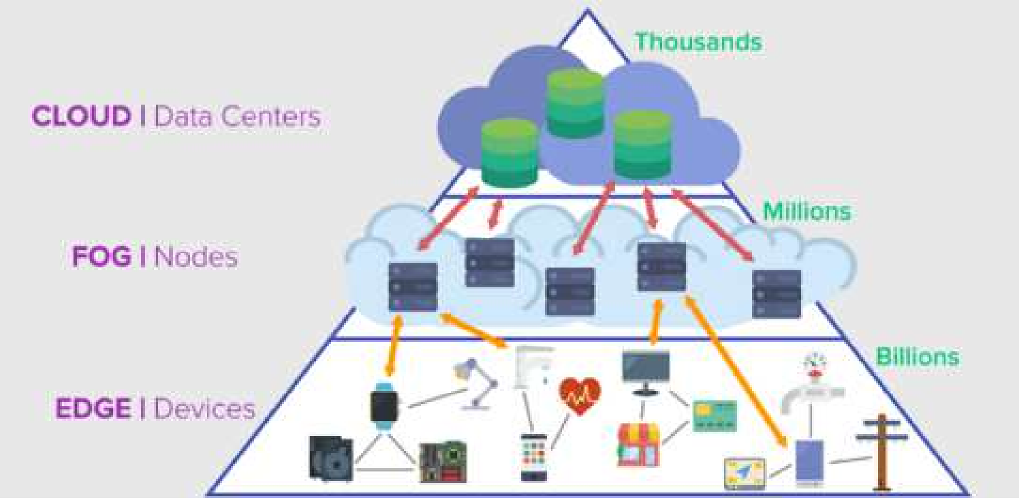

Figure 4 The relationship between cloud computing, edge computing, and fog computing [7].

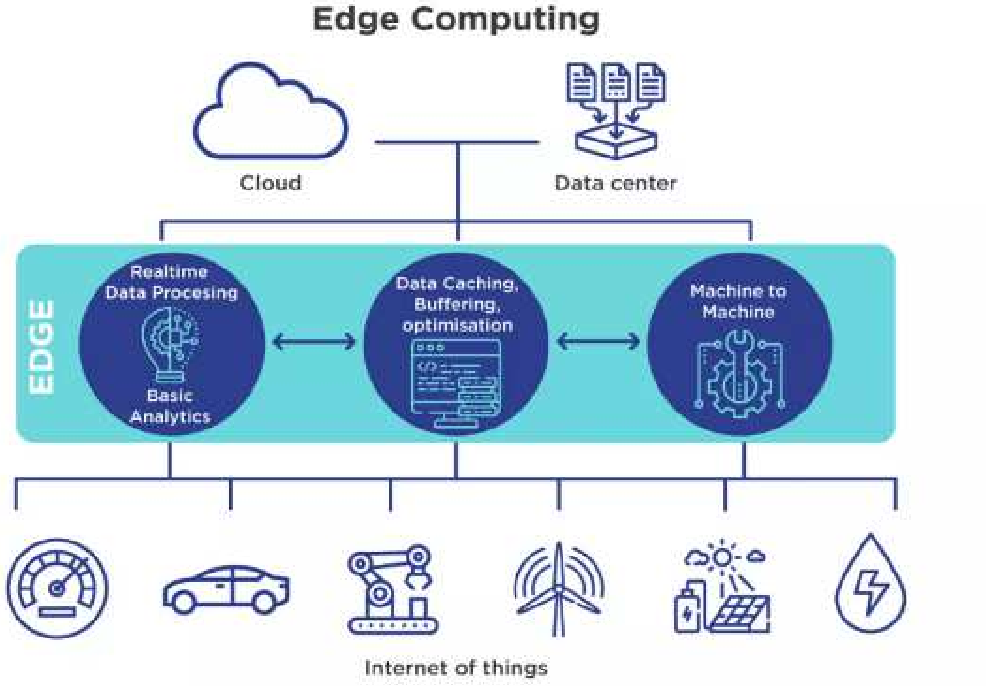

Figure 5 Edge computing [9].

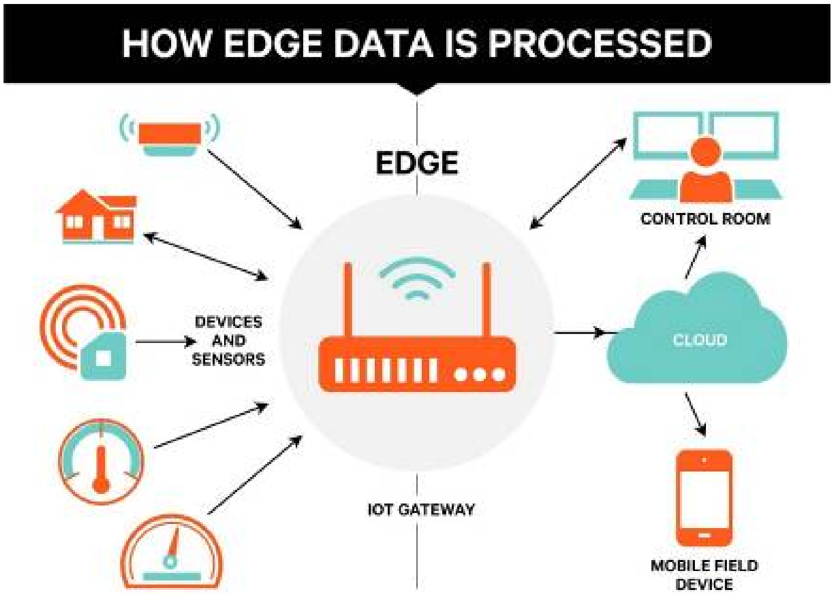

Figure 6 How edge data is processed [3].

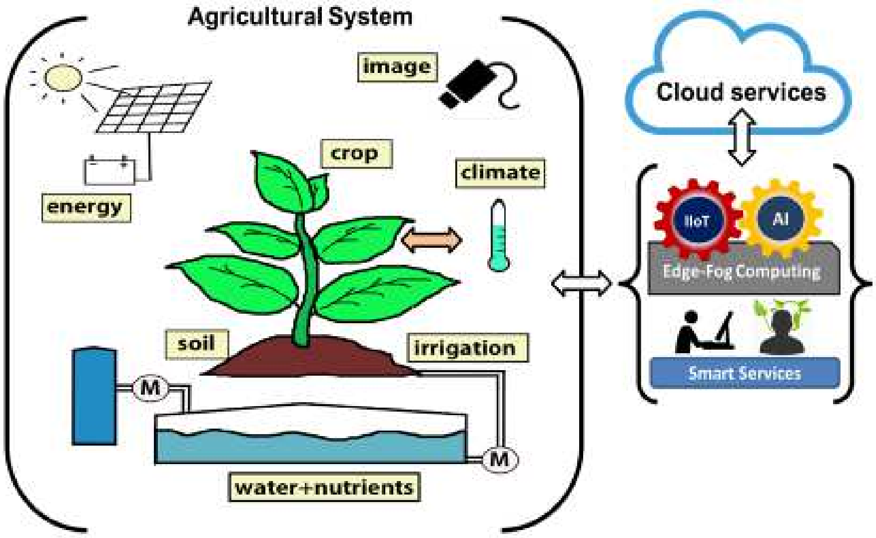

Figure 7 A representation of edge computing in agriculture [10].

Figure 8 A farmer [11].

Figure 9 Smart agriculture [12].

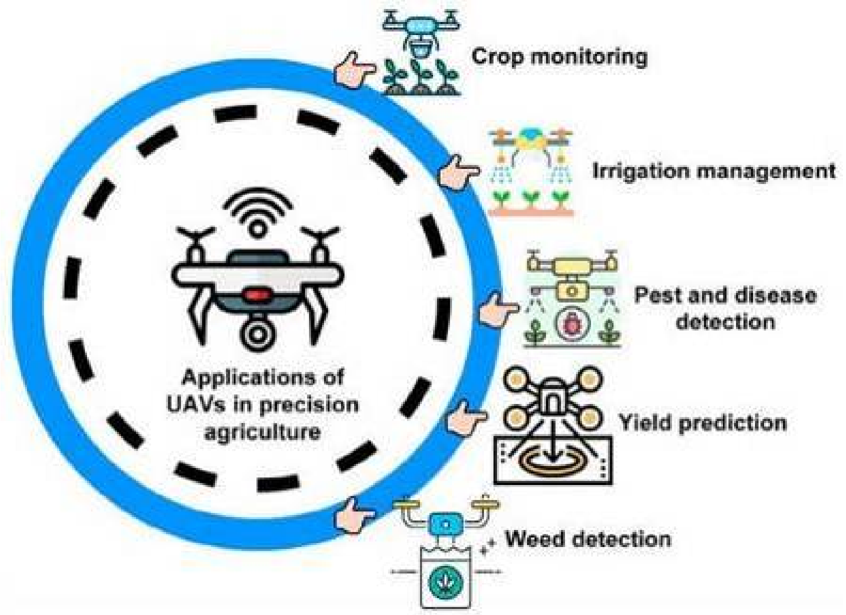

Figure 10 Applications of UAVs in precision or smart agriculture [13].

Figure 11 A self-driving vehicle [11].

Figure 12 An irrigation system [11].