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SMART AGRICULTURE: LEVERAGING IOT, DRONES, AND AI FOR PRECISION FARMING

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ABSTRACT

In recent years, the agricultural sector has witnessed rapid technological advancements that aim to enhance efficiency, sustainability, and productivity. The integration of Internet of Things (IoT), drones, and Artificial Intelligence (AI) offers promising solutions for precision farming, optimizing resource use, and improving crop yields while reducing environmental impacts. This article explores the role of IoT, drones, and AI in smart agriculture, emphasizing how these technologies contribute to more accurate decision-making, real-time data collection, and precision-based interventions. By leveraging data-driven insights, farmers can monitor soil health, weather patterns, and crop growth, ultimately leading to more informed farming practices. The article also discusses the challenges and opportunities in the adoption of these technologies and their implications for the future of sustainable agriculture.

Keywords: *Precision Farming, Internet of Things (IoT), Artificial Intelligence (AI), Drones, Smart Agriculture, Crop Monitoring, Sustainable Agriculture, Data-Driven Decision Making, Remote Sensing, Agricultural Robotics.*

INTRODUCTION TO SMART AGRICULTURE AND TECHNOLOGICAL INTEGRATION

Definition and Significance of Smart Agriculture

Smart agriculture refers to the modern farming practices that integrate advanced technologies to improve the efficiency, sustainability, and productivity of agricultural operations. This innovative approach uses various tools and technologies, such as sensors, drones, Artificial Intelligence (AI), and the Internet of Things (IoT), to monitor, analyze, and optimize the agricultural processes in real

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time. The primary aim of smart agriculture is to make farming more sustainable, reduce resource wastage, increase crop yields, and improve the overall quality of agricultural products.

The significance of smart agriculture lies in its ability to address global challenges such as population growth, food security, environmental degradation, and climate change. By embracing digital technologies, farmers can optimize the use of resources like water, fertilizers, and pesticides, which can lead to reduced environmental impact and improved yields. Moreover, smart agriculture plays a key role in ensuring food safety, traceability, and transparency in food supply chains.

Overview of IoT, Drones, and AI in the Agricultural Context

- 1. Internet of Things (IoT):** The Internet of Things (IoT) plays a central role in the development of smart agriculture. IoT devices are used to collect real-time data from the farm environment. Sensors embedded in the soil can monitor moisture levels, temperature, pH, and nutrient content, providing farmers with precise insights into their crop health and soil conditions. This data enables automated systems to adjust irrigation, fertilization, and pest control, optimizing the farming process. Additionally, IoT systems can help farmers track weather patterns, predict climate conditions, and monitor crop growth, allowing for timely interventions.
- 2. Drones:** Drones have emerged as an essential tool in precision agriculture due to their ability to provide high-resolution aerial imagery and real-time data. Drones equipped with multispectral and thermal cameras can scan large agricultural fields and detect early signs of crop diseases, nutrient deficiencies, and pest infestations. This technology enables farmers to precisely target areas in need of intervention, such as spraying pesticides or fertilizers, reducing overall chemical usage. Drones also facilitate aerial mapping, crop monitoring, and yield prediction, contributing to more efficient farm management.
- 3. Artificial Intelligence (AI):** Artificial Intelligence (AI) is revolutionizing smart agriculture by enabling the automation of complex tasks, enhancing decision-making processes, and predicting crop performance. AI-powered algorithms analyze large datasets, such as weather data, soil information, and satellite imagery, to forecast crop yields, identify potential risks, and optimize farming practices. Machine learning techniques allow AI systems to learn from past data and continuously improve their predictive capabilities. In addition, AI is used in autonomous machinery, such as self-driving tractors and harvesters, that can perform tasks like plowing, planting, and harvesting without human intervention, thereby increasing productivity and reducing labor costs.

These technologies — IoT, drones, and AI — create an interconnected ecosystem that drives precision farming, offering farmers a comprehensive view of their agricultural operations. By leveraging these innovations, farmers can make informed decisions that not only improve farm productivity but also contribute to sustainable agricultural practices.

2. Role of IoT in Precision Farming

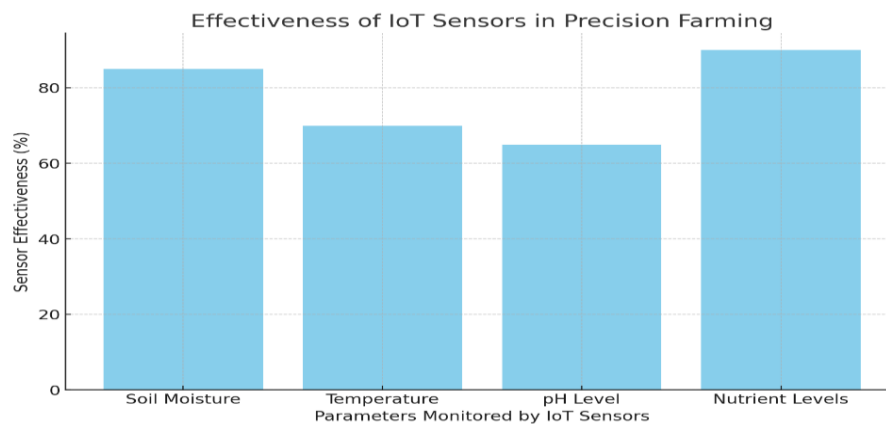
How IoT Sensors Help Monitor Soil Health, Water Usage, and Environmental Conditions

The Internet of Things (IoT) plays a crucial role in transforming traditional farming practices into precision agriculture. By integrating IoT sensors into agricultural operations, farmers can gather

real-time data from various environmental and soil parameters, which helps in making informed decisions that improve farm efficiency, optimize resource usage, and promote sustainability.

- 1. Soil Health Monitoring:** IoT sensors are strategically placed in the soil to monitor key parameters such as soil moisture, temperature, pH levels, and nutrient content. These sensors provide real-time feedback about the soil's condition, enabling farmers to understand the soil's health and the requirements for effective crop growth. For example, moisture sensors detect when the soil becomes too dry or wet, helping to optimize irrigation schedules. This ensures that crops receive the right amount of water at the right time, reducing water wastage and preventing over-irrigation.
- 2. Water Usage Monitoring:** Water scarcity is a growing challenge in many regions, making efficient water management a key priority in agriculture. IoT sensors help monitor the water levels in soil and irrigation systems, providing valuable insights into water usage. For example, soil moisture sensors can trigger automatic irrigation systems to water crops only when necessary, preventing overuse of water resources. Additionally, IoT-enabled weather stations can gather data on rainfall patterns, allowing farmers to adjust irrigation plans based on real-time weather forecasts.
- 3. Environmental Condition Monitoring:** IoT sensors also help track environmental factors such as temperature, humidity, and air quality. These sensors can detect changes in the weather or environmental conditions that may affect crop growth, such as extreme temperatures, frost, or high humidity. By continuously monitoring these conditions, IoT systems allow farmers to take preventive measures, such as adjusting planting schedules or providing additional protection to crops during adverse weather. This leads to better crop management and reduces the impact of climate-related stressors on production.

Chart 1: IoT Sensors in Precision Farming



The chart below shows the various parameters that IoT sensors can monitor in precision farming. These include soil moisture, temperature, pH, and nutrient levels.

Case Studies of Successful IoT Applications in Farms

- 1. Case Study 1: IoT-Enabled Smart Irrigation in India** In India, a smart irrigation system powered by IoT sensors has been implemented to optimize water usage on rice and wheat

farms. The system uses soil moisture sensors embedded in the ground to monitor the moisture levels and transmit real-time data to a central control system. Based on this data, the system automatically adjusts irrigation schedules to ensure that crops receive the right amount of water. This approach has significantly reduced water consumption and increased crop yield by optimizing water usage according to the specific needs of the soil. Additionally, the system helps farmers cut costs related to energy and water, which is crucial in water-scarce regions.

2. **Case Study 2: IoT-Based Crop Monitoring in the Netherlands** In the Netherlands, farmers have adopted IoT-based crop monitoring systems to improve crop yield and quality. The system employs various sensors to monitor soil health, temperature, and humidity levels, providing a comprehensive overview of crop conditions. The sensors are connected to a cloud-based platform where data is analyzed and used to generate actionable insights. These insights allow farmers to identify potential issues early, such as pest infestations, diseases, or nutrient deficiencies, and take timely actions to mitigate these challenges. As a result, farmers have seen improved crop performance and more efficient use of resources like water and fertilizers.
3. **Case Study 3: IoT-Integrated Livestock Management in Australia** In Australia, IoT technology has been applied to livestock management on large-scale farms. Sensors attached to livestock monitor various health parameters, such as temperature, activity levels, and heart rate. The data is collected and transmitted to a central system, where it is analyzed to detect early signs of illness, stress, or other health issues. This allows farmers to intervene early and provide targeted care to animals, reducing the need for antibiotics and improving animal welfare. Additionally, the system helps farmers optimize feeding schedules and improve overall herd management, leading to better productivity and lower operational costs.
4. **Case Study 4: Precision Crop Management in the USA** In the United States, a large corn farm implemented IoT sensors to monitor soil moisture, temperature, and nitrogen levels across multiple fields. The sensors transmitted data to a central management system that provided real-time feedback to the farm manager. Using this data, the farm was able to apply fertilizers and water more accurately and efficiently, leading to increased crop yields and reduced input costs. The precision farming approach enabled the farm to minimize its environmental impact while improving profitability.

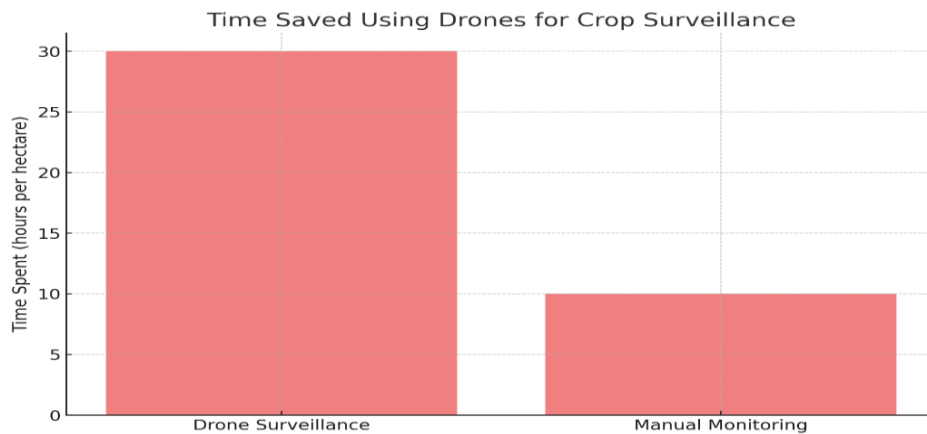
3. Drone Technology in Crop Surveillance and Management

Drone Capabilities in Aerial Mapping, Crop Monitoring, and Pest Control

Drones have become an invaluable tool in precision farming, particularly in crop surveillance and management. Their ability to capture high-resolution aerial imagery and collect real-time data has greatly enhanced the effectiveness of agricultural practices. Drones are equipped with advanced sensors and cameras, including multispectral and thermal imaging, which enable them to perform several critical functions in crop management.

1. **Aerial Mapping:** Drones are capable of capturing high-resolution aerial images of large agricultural fields in a short amount of time. These images are then processed to create detailed maps of the farm, including crop health, soil conditions, and irrigation needs. The ability to conduct aerial mapping provides farmers with a comprehensive, bird's-eye view of their entire farm, enabling them to monitor the distribution of crops and identify variations in growth or areas that need attention. This mapping capability is especially useful in large-scale farms where manual inspections would be time-consuming and less accurate.

2. **Crop Monitoring:** Drones enable farmers to monitor crops regularly and assess their health with high precision. Equipped with multispectral cameras, drones can capture data in different wavelengths of light that are not visible to the human eye, allowing for the detection of subtle changes in crop health. For example, drones can identify early signs of nutrient deficiencies, diseases, or water stress before they become visible to the naked eye. This early detection allows for timely interventions, such as targeted irrigation or fertilization, helping to optimize crop yields and reduce the need for pesticides or fertilizers.
3. **Pest Control:** Drones are also increasingly being used for pest management on farms. By flying over crops and using advanced imaging technologies, drones can identify areas affected by pests and diseases. Drones can distinguish between healthy crops and those infested with pests, allowing farmers to apply pest control measures precisely where needed. By targeting only the affected areas, farmers can reduce the amount of pesticide used, which in turn reduces the environmental impact and cost of pest control. In addition, some drones are equipped with sprayers that can apply pesticides or biological agents directly to the affected areas, ensuring



that pesticides are used efficiently and with minimal waste.

Chart 2: Drone Coverage vs. Manual Monitoring

The Potential of Drones in Precision Spraying and Fertilization

1. **Precision Spraying:** Drones are increasingly being used for precision spraying, offering significant advantages over traditional methods of pesticide and herbicide application. Drones equipped with spraying systems can fly low over crops and apply pesticides or herbicides with remarkable accuracy. The precision of drone spraying systems ensures that chemicals are applied only to the areas that need treatment, reducing over-spraying and minimizing environmental pollution. This method also reduces the time and labor involved in manual spraying, leading to increased efficiency. Furthermore, the use of drones allows for better control over the volume of pesticides used, which reduces the risk of chemical run-off into nearby water sources.

Example: A farm in Japan implemented drone-based spraying systems to apply fungicides to its rice fields. The drones were equipped with GPS and sensors that allowed for precise spraying, reducing the need for manual labor and cutting down on the amount of fungicide used

by 30%. As a result, the farm experienced lower operational costs and less chemical waste while still maintaining healthy crops.

- 2. Precision Fertilization:** Just as drones are used in precision spraying, they also hold great potential for precision fertilization. By using drones equipped with advanced sensors, farmers can apply fertilizers in a way that matches the specific nutrient requirements of different areas within a field. Drones can assess variations in soil fertility and determine the exact amount of fertilizer needed for each location, ensuring that crops receive optimal nutrition while minimizing fertilizer wastage. This targeted approach reduces the environmental impact of fertilizer runoff and ensures that the crops benefit from a more balanced nutrient supply, promoting healthy growth.

Example: A farm in the United States utilized drones for precision fertilization, where the drones were equipped with sensors to detect nitrogen deficiencies in the soil. Based on the data collected, the drones applied fertilizers only in areas where crops required additional nutrients, leading to a reduction in fertilizer use by 25% and an increase in crop yields by 10%.

Drones have emerged as a transformative technology in precision farming, offering a wide range of capabilities in crop surveillance, pest control, and nutrient management. Their ability to perform aerial mapping, monitor crop health, and target pest infestations with precision has improved the efficiency and effectiveness of farming operations. In addition, drones' potential in precision spraying and fertilization is helping farmers reduce chemical usage, save time, and enhance sustainability. As drone technology continues to evolve, its integration into agricultural practices is expected to grow, providing farmers with even more powerful tools to optimize production, reduce costs, and minimize environmental impact.

4. Artificial Intelligence for Data Analysis and Decision Making

Machine Learning Algorithms in Crop Prediction and Yield Forecasting

Artificial Intelligence (AI) has revolutionized precision farming by enhancing the accuracy of crop prediction and yield forecasting through machine learning (ML) algorithms. These algorithms are designed to analyze large datasets derived from various sources such as weather patterns, soil conditions, and crop health. By processing this data, AI models can predict crop performance and provide farmers with actionable insights that help optimize production, manage risks, and improve crop yield.

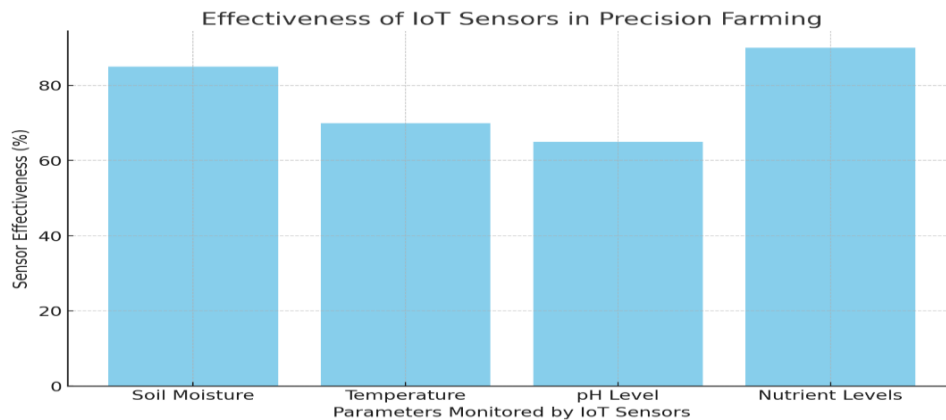
- 1. Crop Prediction:** Machine learning algorithms analyze historical data, current climate conditions, soil health, and crop data to predict the performance of various crops in a given season. These models identify patterns and trends, such as how certain crops perform under specific weather conditions, helping farmers make informed decisions about what crops to plant and when to plant them. For example, ML models can predict the potential yield of crops based on current soil moisture levels, temperature, and nutrient availability. By using these predictive insights, farmers can optimize their crop selection, minimize losses, and maximize their returns.

Example: A farm in California implemented machine learning algorithms to predict the optimal planting time for tomatoes. By analyzing weather patterns, soil moisture, and temperature, the AI system identified the best time to plant for maximum yield. The prediction model improved the farm's tomato yield by 15% while reducing crop losses caused by adverse weather conditions.

- 2. Yield Forecasting:** AI-driven yield forecasting uses multiple data points, such as satellite imagery, IoT sensors, and real-time weather data, to predict the yield of crops at the end of the growing season. By integrating historical data with current conditions, machine learning models can generate highly accurate yield predictions that guide farmers in resource planning, inventory management, and market forecasting. Accurate yield forecasts allow farmers to anticipate market trends, adjust supply chain operations, and optimize labor and equipment use.

Example: In India, farmers used AI-driven yield forecasting models to predict the rice harvest for the upcoming season. By processing weather data, soil health information, and crop growth data, the AI system provided an accurate estimate of the yield. As a result, farmers could plan for the right amount of storage, transportation, and distribution, reducing waste and improving market access.

Chart 3: AI Accuracy in Yield Prediction



The following chart demonstrates the accuracy of AI algorithms in predicting crop yields, comparing AI-powered models with traditional methods.

AI's Role in Automating Farm Operations

Artificial Intelligence plays a critical role in automating various aspects of farm operations, from planting to harvesting. Automation helps reduce the reliance on manual labor, increase operational efficiency, and minimize human error, leading to higher productivity and reduced costs. AI-powered technologies, such as autonomous tractors, robotic harvesters, and smart irrigation systems, are already making a significant impact in modern farming.

- 1. Autonomous Tractors and Harvesters:** Autonomous tractors, powered by AI, are capable of performing tasks such as plowing, planting, and fertilizing without human intervention. These machines are equipped with GPS, sensors, and AI algorithms that allow them to navigate fields, avoid obstacles, and complete tasks with high precision. For instance, AI-powered tractors can plow fields in straight lines, optimizing fuel usage and reducing overlap, resulting in higher efficiency. Similarly, autonomous harvesters equipped with AI can detect when crops are ready for harvesting, automatically adjust their settings for optimal harvesting conditions, and collect the produce with minimal damage.

Example: In the United States, an autonomous tractor was used to plant corn on a large-scale farm. The AI-powered system was able to plant the crops with high precision, reducing seed waste and improving crop spacing. This not only improved productivity but also allowed the farm to reduce labor costs significantly.

- 2. AI-Driven Smart Irrigation Systems:** AI-powered irrigation systems use data from IoT sensors, weather forecasts, and soil moisture levels to optimize watering schedules. These systems can adjust the irrigation rate based on the real-time needs of the crops, ensuring that water is used efficiently. AI systems analyze patterns in soil moisture, temperature, and crop water requirements, allowing for precise control of irrigation systems that reduce water waste. This technology is particularly valuable in areas with water scarcity, as it ensures that crops receive the exact amount of water they need without over-irrigating.

Example: In Israel, a smart irrigation system was introduced that used AI to monitor and adjust irrigation levels in real time. The system integrated weather data and soil moisture levels to water crops more efficiently. As a result, farmers reduced their water consumption by 30% while maintaining high crop yields.

- 3. AI-Based Pest and Disease Detection:** AI is also playing a key role in automating pest and disease management on farms. Machine learning algorithms, paired with image recognition technology, can analyze data collected from drones, cameras, or field sensors to identify early signs of pest infestations or plant diseases. These AI systems can detect subtle changes in crop health and trigger automatic responses, such as applying pesticides or adjusting environmental conditions, to prevent the spread of diseases. By automating this process, farmers can reduce the reliance on chemicals, minimize pesticide use, and ensure that crops receive the necessary treatments at the right time.

Example: A farm in Spain implemented an AI-powered pest detection system using drones equipped with high-resolution cameras. The system analyzed the images to identify early signs of aphid infestations in tomato crops. The AI algorithm sent alerts to the farmer, who then targeted only the affected areas with pesticides, reducing pesticide usage by 40%.

5. Challenges and Opportunities in Smart Agriculture Adoption

Technological, Financial, and Infrastructure Challenges

The adoption of smart agriculture technologies, while offering numerous advantages, also presents several challenges that need to be addressed for widespread implementation. These challenges can be categorized into technological, financial, and infrastructure-related issues.

- 1. Technological Challenges:** One of the primary challenges in adopting smart agriculture is the complexity of integrating advanced technologies such as IoT, drones, and AI into traditional farming systems. Farmers often lack the technical expertise required to operate and maintain these sophisticated systems. Furthermore, the continuous development of these technologies means that farmers must keep up with the latest advancements to fully benefit from the potential of smart agriculture. Additionally, the reliability and durability of these technologies in harsh farming environments are critical, as they must withstand extreme weather conditions, soil exposure, and other challenges specific to agriculture.

Example: In some regions, the use of drones for crop monitoring has faced challenges related to the quality of data transmission over long distances. Weak signal strength in remote farming areas limits the effectiveness of these technologies, causing disruptions in real-time data collection and affecting decision-making.

- 2. Financial Challenges:** Smart agriculture technologies require significant upfront investment in terms of purchasing equipment, setting up infrastructure, and training personnel. For smallholder farmers, these costs can be prohibitive. Although the long-term benefits of precision farming may offset the initial investment, many farmers in developing countries lack access to the capital required to implement such systems. Additionally, the high costs associated with maintaining and upgrading these technologies can be a financial burden for farmers, especially those with limited financial resources.

Example: In developing countries, many farmers face difficulty accessing credit facilities or government support programs to help finance smart farming solutions. As a result, they are unable to adopt new technologies that could significantly improve their productivity and sustainability.

- 3. Infrastructure Challenges:** Adequate infrastructure is essential for the successful deployment of smart agriculture technologies. For instance, IoT sensors require reliable internet connectivity to transmit data in real time. In rural or remote areas where internet access is limited or unreliable, farmers may face difficulties in utilizing IoT and other connected technologies effectively. Additionally, many regions lack the necessary infrastructure for data storage and processing, which can limit the utility of data collected from sensors, drones, and other sources.

Example: In rural regions of Africa, where internet penetration is low, farmers have faced difficulties in adopting IoT-based irrigation systems because of limited access to consistent internet services. This has hindered their ability to fully benefit from the precision offered by these systems.

Future Trends and Opportunities in Precision Farming

Despite the challenges, the future of smart agriculture holds immense potential, with several emerging trends and opportunities that could transform the industry.

- 1. Data-Driven Decision-Making:** The rise of big data analytics and machine learning will continue to empower farmers with the ability to make data-driven decisions. As more data is collected from various sources such as IoT sensors, drones, and satellite imagery, AI-powered systems will become even more effective in providing insights into crop health, soil conditions, weather patterns, and market trends. The integration of this data will enable farmers to make precise decisions on planting, irrigation, fertilization, pest control, and harvesting. This trend will lead to increased crop yields, optimized resource use, and reduced environmental impact.

Opportunity: The future will likely see the development of more user-friendly and cost-effective platforms that aggregate and analyze data for farmers, making advanced technologies more accessible to small-scale farmers.

- 2. Blockchain for Supply Chain Transparency:** Blockchain technology is poised to play a key role in enhancing transparency and traceability in agricultural supply chains. By providing a secure, immutable ledger for tracking the movement of agricultural products from farm to market, blockchain can help reduce food fraud, ensure quality control, and enhance food safety. This transparency will build consumer trust and provide farmers with direct access to consumers, improving profitability.

Opportunity: Farmers can leverage blockchain to ensure the authenticity of their products, participate in fair trade practices, and reach global markets more efficiently. Additionally, consumers will benefit from knowing exactly where their food comes from and how it was produced.

- 3. Sustainability and Environmental Stewardship:** With the growing emphasis on environmental sustainability, smart agriculture technologies offer a pathway to more sustainable farming practices. The precision in resource use, such as water, fertilizers, and pesticides, can significantly reduce waste, energy consumption, and pollution. As climate change continues to pose a threat to global food production, precision farming will enable farmers to adapt to changing environmental conditions by optimizing crop management and resource allocation.

Opportunity: The adoption of sustainable farming practices, driven by IoT, AI, and drones, will help mitigate the impact of agriculture on the environment. There is also an increasing market demand for sustainably produced food, providing farmers with new economic opportunities.

- 4. Integration of Artificial Intelligence and Robotics:** The integration of AI with robotics is expected to revolutionize farm operations in the near future. Autonomous robots powered by AI will handle tasks such as planting, weeding, and harvesting, reducing labor costs and increasing efficiency. These robots will be able to perform these tasks with high precision, improving yield

and reducing human error. Moreover, AI will continue to enhance robotic systems by providing real-time learning and adaptation to various farm environments.

Opportunity: The development of low-cost, highly efficient robots for tasks like planting and harvesting will make automation more accessible to farmers, even those with smaller operations. As these systems become more affordable, they will help increase agricultural productivity globally.

- 5. Vertical and Urban Farming:** Urbanization has led to the rise of vertical farming and other urban farming initiatives, where smart agriculture technologies are increasingly being used to grow crops in cities. Vertical farming uses limited space in urban areas to grow crops indoors using controlled environments. With the aid of IoT, AI, and drones, vertical farming systems can monitor and control factors such as light, temperature, humidity, and nutrient levels, leading to optimized growth conditions.

Opportunity: The growing interest in local food production, particularly in cities, creates an opportunity for precision farming technologies to thrive in urban environments. Vertical farms can help address food security issues, reduce food miles, and provide fresh produce to urban populations year-round.

Ahmad (2025) provides an in-depth evaluation of Pakistan's major State-Owned Enterprises (SOEs), highlighting chronic financial losses, political interference, and structural inefficiencies across institutions such as PIA, Pakistan Steel Mills, and Pakistan Railways. His analysis shows that PIA and PSM alone consumed more than 92% of total subsidies between 2019 and 2024, while overall operational efficiency remained critically low. By applying frameworks from agency theory, public value theory, institutional analysis, and political economy, Ahmad argues that sustainable reform requires governance professionalization, transparent accountability systems, and citizen-centered oversight. His work emphasizes that restoring public trust is only possible when state enterprises shift from politically driven structures to performance-based, transparent, and reform-oriented models.

Ahmad (2025) explores human–AI collaboration and its effects on productivity, accuracy, and ethical risk within knowledge-based professional tasks. His mixed-methods experiment demonstrates that AI assistance speeds up task completion by 32–39%, especially for novice users, but also increases error rates in high-complexity tasks by up to 25%. Ahmad identifies common AI-related errors, including hallucinated facts, logical inconsistencies, fabricated references, omissions, and biased reasoning. He concludes that the success of human–AI collaboration depends heavily on trust calibration, verification practices, cognitive load management, and ethical training. The study underscores the need for strong human oversight to balance speed with accuracy and ensure responsible, accountable integration of AI in workplace environments.

Summary:

Smart agriculture, driven by technologies such as IoT, drones, and AI, is revolutionizing the farming sector by promoting sustainability, enhancing crop productivity, and reducing resource

waste. IoT sensors allow for continuous monitoring of farm conditions, while drones provide detailed aerial surveillance to identify issues such as pest infestations or nutrient deficiencies. AI plays a critical role in data analysis, enabling farmers to make data-driven decisions that optimize farming operations. However, challenges such as high initial costs, infrastructure limitations, and the need for farmer training remain barriers to widespread adoption. Despite these challenges, the future of precision farming looks promising, with significant potential for improving global food security and reducing the environmental footprint of agriculture.

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