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Exploring the Role of Smart Systems in Farm Machinery for Soil Fertility and Crop Productivity

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Abstract: Agriculture is experiencing a period of technological change, driven by the addition of intelligent technologies into agricultural technology. The integration of smart systems into farm machinery has greatly improved soil fertility management and crop productivity. Advanced technologies such as sensors, IoT, AI, and precision agriculture tools enable real-time monitoring of critical soil parameters, leading to targeted interventions for improving soil health. Automated machinery with GPS and AI-driven algorithms ensures efficient seed placement, precise fertilizer application, and weed management, thereby minimizing resource wastage and environmental impact. Such insights based on data allow farmers to take appropriate decisions based on changing conditions and improve farming practices sustainably, but their large-scale adaptation can be impeded due to high implementation costs, issues with privacy over the data, and expertise over technicalities. But even these challenges are seen in light of increasing yield, input costs reduced, and sustainability-promoting benefits, thereby raising productivity and meeting the causes for environmental conservation and food security.

Keywords: Precision agriculture, Soil fertility, Smart farming systems, Crop yield enhancement, Internet of things (IoT), Artificial intelligence (AI)

I. INTRODUCTION

The foundation of human civilization, agriculture, is facing hitherto unheard-of difficulties in the twenty-first century. By 2050, the world's population is expected to have grown to around 10 billion people, necessitating a major increase in food production [1]. However, this work needs to be done in the face of declining arable land, degraded soil, and growing climate change effects [2]. For the agriculture sector to overcome these obstacles and maintain environmental stewardship and productivity, creative and sustainable solutions are needed.

A. *The Importance of Soil Fertility and Crop Productivity*

Agriculture's two main pillars are crop productivity and soil fertility. The ability of soil to supply crops with essential nutrients is known as soil fertility, and it has a direct impact on both the amount and quality of output [3]. Significant soil degradation has resulted from overuse of arable land as well as unsustainable agricultural methods, including excessive fertilizing and inappropriate irrigation. Crop yields are decreased by poor soil health. This impacts farmer livelihood sand food security. The yield that can be obtained per unit of land, however, is known as crop productivity [4]. Increased productivity without further arable land development is crucial if one does not wish to eliminate trees from a forest or, at the very least, reduce biodiversity. Increased output with traditional techniques, including unrestrained use of pesticides, fertilizers, and irrigation, is harmful to the environment and inefficient. Techniques for yields that are more sustainable and highly effective must be found quickly.

B. *Emergence of Smart Systems in Agriculture*

This new paradigm in agricultural practice makes way for the shift towards intelligent systems in farming. The smart systems make use of all the latest technologies to help solve specific needs in soil and crops with more error-free data-driven information than traditional techniques, which are intuitive and equal division of resources.

In order to improve agricultural operations, smart farm machinery integrates advancements like artificial intelligence, big data analytics, GIS, and the Internet of Things [5]. These devices allow for the most effective use of water, fertilizer, and pesticide inputs; they also enable the real-time, accurate monitoring of field conditions, and they mechanize several repetitive tasks, such as planting and harvesting.

Thus, farm output will increase substantially due to this type of integration of technology, but without some corresponding reduction in environmental degradation along with depleting critical resources.

C. The Role of Smart Systems in Soil Fertility and Crop Productivity

The smart soil fertility system [6], installed on farms and self-motoring equipment, provides real-time pH and moisture status reports. Based on the circumstances being monitored, the system then adjusts intervention into particular farm parts. VRT precisely applies fertilizers and ameliorants to agricultural soils, utilizing all nutrients and generating minimal waste [7]. Site-specific management is made possible by the use of geospatial tools to create detailed soil maps that display spatial changes within fields. Additionally, smart systems contribute to increased crop output [8]. Using AI- and IoT-based technologies, precise agriculture makes sure that the right number of plants are planted, when to water them, and how to handle pests [9]. This minimizes losses and increases yields. Drones and autonomous machinery enhance operational efficiency by ensuring high-resolution field data for quick decision-making and automating manual tasks [10].

D. Objectives of The Review

The review explores the integration of smart systems in farm machinery to improve soil fertility and crop productivity. It focuses on the fundamental technologies like IoT, AI, robotics, and geospatial tools that form the basis of smart farming systems. These technologies can address challenges like resource inefficiency, environmental degradation, and the growing demand for food production. However, the review also identifies limitations like high costs, data privacy concerns, and technical expertise requirements that may hinder large-scale adoption. A case study is included to illustrate the real-world impact of these smart systems, highlighting their potential to address global agricultural issues. The paper aims to demonstrate how smart farming can achieve sustainability and food security through innovative agricultural practices and future trends.

II. TECHNOLOGICAL FRAMEWORK OF SMART SYSTEMS IN AGRICULTURE

Traditional farming methods have been replaced by precision, automation, and data-driven decision-making processes as a result of the agriculture sector's use of intelligent technologies. These systems are built on a broad technological framework that seeks to improve soil fertility and boost crop yields by combining a number of advanced instruments and methods. The key components of such an infrastructure are discussed below:

A. Internet of Things in Agriculture

The internet of things is completely changing agriculture by connecting various sensors, devices, and equipment to create a network for real-time data collection and communication [11]. IoT sensors track soil parameters like pH levels, moisture, temperature, and nutrient content, which are transmitted to a centralized system for site-specific interventions [12]. Weather monitoring is another crucial application, with IoT-enabled weather stations gathering localized data to help farmers plan irrigation schedules, pest control strategies, and optimal planting times. IoT devices also monitor livestock health and behavior, minimizing disease risks and ensuring efficient feeding practices. IoT reduces manual labor through automation, such as intelligent irrigation systems that adjust water delivery based on soil moisture levels, ensuring crops receive the right amount of water while conserving resources [13], [14]. This precision reduces waste, improves crop yield, and enhances overall farm productivity [15]. IoT-based automation improves accuracy while decreasing manual labor, such as intelligent irrigation systems that conserve resources while preserving ideal growing conditions for crops. **Fig. 1** illustrates the diverse applications of IoT across various agricultural domains. It emphasizes how IoT-enabled sensors and devices contribute to real-time data collection and precision farming, enabling resource optimization and improved productivity.

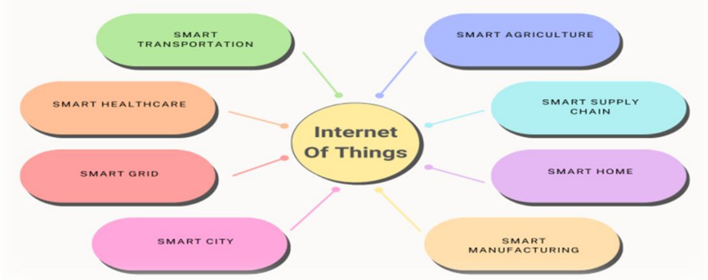

Fig. 1 Uses of IoT in different areas

B. *Artificial Intelligence and Machine Learning*

Using agricultural data, it assists in finding trends and forecasting results before recommending them to AI and ML systems. This gives the farmer the ability to make decisions that go beyond gut instinct [16], [17]. There are several key applications showing below:

1) *Analytics that predict:* AI makes preventive treatments possible by forecasting crop illnesses, insect outbreaks, and weather changes [18]. This allows farmers to take timely preventive measures, reducing losses and improving yields. For example, AI systems in vineyards can detect early signs of fungal infections, enabling immediate intervention and preventing widespread damage.
2) *Crop management:* AI uses field-based data to determine the optimal periods for seeding, crop rotation, and fertilizer application rates. This precision reduces resource wastage while maximizing growth potential. For example, AI algorithms recommend the best crop rotation plans based on soil health and weather predictions [19].
3) *Yield estimation:* To assist farmers in organizing harvests and marketing plans, machine learning models employ both historical and current data to estimate yields. These predictions help farmers plan harvests, optimize storage, and develop marketing strategies [20]. For example, in rice fields, AI predicts insect outbreaks with over 90% accuracy, ensuring timely application of pesticides [21]. Fig. 2 highlights the role of AI and ML in enabling precision agriculture. It illustrates key applications such as predictive analytics, crop management, and yield estimation, showcasing how data-driven technologies optimize farming practices.

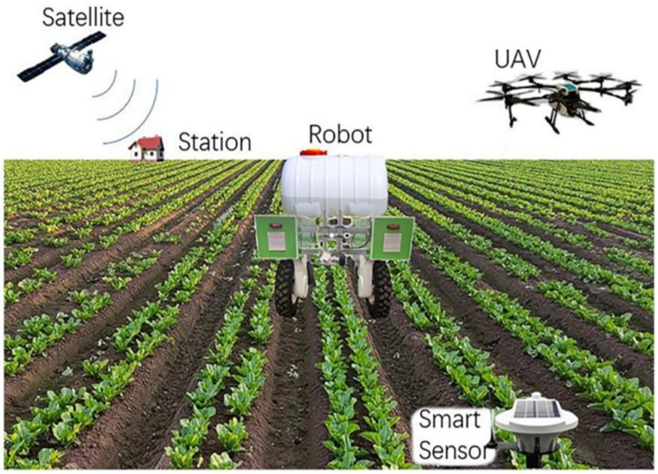

Fig. 2 Artificial intelligence and machine learning in precision agriculture [22]

C. *Geospatial Technologies: GIS and GPS*

The core geospatial technologies, GIS and GPS, are examples of further such technologies. They offer high-accuracy mapping and spatial data for each segment of a field. Agricultural GIS Detailed maps of soil properties, crop health, and field variability are created by GIS technologies processing satellite photos, drone videos, and field data [23]. These serve as site-specific management guidelines that guarantee resource distribution.

1) *GPS in equipment:* Precision in planting, fertilizing, and harvesting is achieved by the use of GPS-guided tractors and harvesters. By minimizing overlap and reducing input waste, productivity is raised and urban connectivity is enhanced[24], [25].
2) *Remote sensing and drones:* Mounting multispectral cameras on unmanned aerial vehicles (drones) allows for the capture of high-resolution photographs of fields [26]. These pictures are useful for assessing insect damage, crop Vigor, and water stress, so treatments can be assessed. be the target.
3) *Geospatial tools benefits:* By detecting field variability and identifying trouble spots, geospatial technologies assist farmers in applying inputs correctly, lowering expenses and their impact on the environment [27].

D. *Analytics of Big Data*

Big data's most crucial function is to handle and interpret the vast amounts of data produced by sensors and IoT devices, as well as by GIS tools that use advanced analytics to turn the data into action for farmers.

1) *Important uses analyzing historical data:* Examining past data on weather patterns, agricultural performance, and soil fertility trends. Some, such as Climate Field View or Farm Logs, offer dashboards that gather a lot of data for decisions, often as basic as when to apply fungicides or water [28].
2) *Supply chain optimization:* Big data reduces post-harvest losses, streamlines inventory management, and connects farm operations to supply networks. The idea of big data analytics is a highly powerful environment for a decision because of its integration with AI and IoT [29]. For example, an examination of meteorological data inputs from soil sensors and crop imaging can be used to provide a fertilization strategy for particular locations.

E. *Robotics and Autonomous Machinery*

Automation and precision are being introduced into farm operations as a result of autonomous machinery and robotics [30]. Autonomous tractors equipped with GPS and AI perform tasks like tilling, planting, and fertilizing with minimal human intervention, ensuring consistent results and reducing human errors [31]. Robotic harvesters automate fruit and vegetable picking, improving timeliness and quality while minimizing labor requirements. Drones play a dual role by monitoring fields with high-resolution imaging and delivering precise pesticide or fertilizer applications, significantly reducing chemical usage and environmental impact [32]. These advancements enhance operational efficiency, lower costs, and ensure scalability, making agriculture more sustainable and adaptable to modern challenges.

F. *Agricultural Traceability Using Blockchain*

Blockchain technology appears to be quite useful for agriculture, despite the fact that it is not yet widely used. Along the farm-to-market supply chain, block chain technology's traceability increases supply chain transparency like seeds, fertilizers, and pesticides, ensuring quality standards and compliance with sustainable practices [33]. It also enables product certification, such as organic or ethical farming labels, which builds consumer trust and adds value to produce. Additionally, blockchain secures data from unauthorized access, ensuring reliable information exchange from farm to market. By fostering accountability and consumer confidence, blockchain creates a more trustworthy and efficient agricultural ecosystem.

G. *Technology Integration*

Here is where full integration will offer real power in intelligent systems. Data is brought in by IoT, interpreted by AI and analytics, and then used by autonomous machines. Block chain builds supply chain confidence, while geospatial tools guarantee precise interventions. In this sense, the combined effects of these technologies enhance the farm's sustainability and productivity.

III. SMART SYSTEM'S ROLE IN SOIL FERTILITY MANAGEMENT

Soil fertility has a direct impact on crop health, growth, and yield. The balance between soil health, nutrient supply, and environmental sustainability is the key to controlling fertility [34].Conventional fertilizer and other amendment applications for soil fertility usually follow a consistent application process, which may result in inefficiency, nutrient imbalances, environmental harm particularly stream contamination or soil degradation. In the face of the aforementioned difficulties, smart systems made possible by advanced technology provide creative answers to the precise, data-driven method of managing soil fertility. **Table 1** outlines the components and benefits of smart systems in improving soil fertility, such as IoT sensors, variable rate technology, and geospatial analysis showcasing the role of smart systems in farm machinery for soil fertility and crop productivity.

Table 1. Smart systems' role in soil fertility

Component	Function	Example applications	Benefits	References
IoT sensors	Real-time soil condition monitoring	Tracking moisture, pH, nutrient levels	Timely interventions, reduced uncertainty	[35]
Variable rate technology	Precision application of inputs	Field-specific fertilizer and lime application	Reduced waste, increased efficiency	[36]
Geospatial analysis	Detailed soil mapping	Identifying erosion-prone areas	Better resource allocation	[37]
AI-based systems	Data-driven recommendations	Fertilizer scheduling, irrigation planning	Enhanced decision-making	[38]
Organic matter management	Preservation of soil organic content	Monitoring carbon sequestration	Improved microbial health, water retention	[39]
Fertilizer optimization	Balanced nutrient application	Custom blends for field-specific needs	Reduced environmental impact	[40]
Erosion management	Minimizing soil loss	Contour plowing, buffer strip placement	Sustained fertility, reduced degradation	[41]

A. Monitoring and Diagnosing Soil in Situ

IoT-based soil sensors allow for real-time soil parameter monitoring through smart systems. These sensors will take measurements and supply information. on important soil health indicators in a timely manner, allowing farmers to determine when actions are required.

1) *Tracked parameters:* In order to regulate irrigation and prevent waterlogging or drought stress, the moisture content of the soil is an extremely important factor to consider [42].
2) *Nutrient Levels:* It helps direct fertilizer applications by tracking the amounts of potassium, phosphorus, and nitrogen. Thus, the pH of the soil keeps microbial activity and nutrient uptake at optimal levels. Root growth and seed germination are impacted by temperature. Benefits Real-time data guarantees that interventions are relevant and timely while lowering uncertainty. For instance, identifying a decrease in soil moisture enables prompt irrigation, so avoiding crop stress [43].

B. Variable Rate Technology

Site-specific fertilizer, lime, and other amendment applications are made possible by variable rate technology. Managing field variability is part of this VRT in order to prevent nutrient waste and over application while maximizing input utilization and enhancing soil fertility [44]. The operation of Artfield variability is mapped using data from GIS technologies, drones, and soil sensors. Field-specific soil requirements are met by applying fertilizers or amendments at varying rates throughout the fields. Accuracy in application is guaranteed by equipment equipped with GPS and automated controllers [45].

1) *Impact on fertility of soils:* In certain places, it stops the accumulation or depletion of nutrients. Increases the efficiency of nutrient usage by using fewer inputs. By lowering the amount of surplus nutrients that leak and discharge into water, it safeguards the ecosystem [46].
2) *VRA maps of nitrogen:* The element nitrogen VRA maps give you a quick overview of the vegetation condition in your field right now [47]. The user can choose which of the single satellite images used to create these the best option is given their current circumstances. This feature is especially helpful for applying nitrogen fertilizer efficiently and precisely, which will address deficiencies that are preventing crops from growing as much in particular parts of your field. For crops like wheat and rapeseed that receive multiple nitrogen applications during overwintering, the use of VRA maps of nitrogen is ideal [48]. Furthermore, the prescription can be added to crop management by using growth regulators in situations when there are high NDVI values.

C. Geospatial Analysis and Soil Mapping

Geospatial technologies like GIS and remote sensing are used to create detailed soil maps that reveal spatial variability within fields. These maps provide insights into nutrient distribution, moisture retention, and erosion-prone areas. In India, rice farmers have optimized fertilizer application using GIS-based soil maps, reducing costs by 20% and improving yield consistency [49]. These maps help farmers allocate resources effectively, ensuring degraded areas receive necessary inputs while conserving resources in healthy zones. Field heterogeneity is highlighted by these maps, which are useful for managing specific sites and highlighting variations in soil fertility. They are used for identifying areas for conservation techniques and erodible portions, providing accurate fertilizer recommendations and determining irrigation schedules based on soil water retention. Large-scale data on crop and soil conditions is captured via satellite imagery, while drones provide local, high-resolution data for in-depth research. Ground-truth remote sensors confirm their accuracy.

D. Accurate Fertilizer Administration

Fertilizer application is transformed by smart systems into an accurate and effective procedure that enhances soil health and lessens its negative effects on the environment.

1) *Strategies for nutrient management:* Split fertilizer application corresponds nicely with crop growth stages. This reduces waste.
2) *Custom blends:* To ensure balanced fertilizer application, composition is blended according to field-specific requirements.
3) *Micronutrient delivery:* This addresses shortages in elements that are essential for crop growth, such as iron, boron, and zinc. Enablers of Technology GPS-enabled automatic sprayers with flow control. Artificial intelligence systems that can recommend fertilizer schedules based on crop requirements, soil data, and weather forecasts. For example, precision fertilization systems in Australian wheat fields improved water quality while maintaining high yields by reducing nitrogen runoff by 30% [50].

E. Management of Erosion and Compaction

Physical issues with soil health are addressed by smart systems, including compaction and erosion. Fertility is significantly influenced by both of these.

1) *Erosion control solutions:* The positioning of buffer strips, contour plowing, and cover crops is guided by GIS-based erosion risk maps. IoT-enabled weather stations forecast when rainfall will increase, allowing farmers to plan their erosion management strategies.
2) *Soil compaction remedy:* The bulk density is measured by smart tractors equipped with soil compaction sensors, which also estimate the level of tillage. The goal of controlled traffic farming (CTF) is to reduce soil compaction caused by machinery by restricting field traffic lanes. Benefits Sustained fertility depends on root penetration, water infiltration, and microbial activity, all of which are improved by maintaining soil structure [51].

F. Management of Organic Matter

These support the preservation or enhancement of soil organic matter, which is critical for microbial health, water retention, and nutrient cycling. Interventions with Technology Drones keep an eye on organic additions, such as charcoal or compost. IoT sensors track carbon sequestration in fields, including residue retention and low tillage [52]. Quantification of the Benefits of Adding Organic Matter encourages farmers to use smart solutions for sustainable soil management.

G. Decision Support System Integration

Decision Support Systems are smart systems that use data from various sources like satellite imagery, weather stations, and soil sensors to provide actionable recommendations on soil fertility and aquaculture management [53]. AI and machine learning algorithms analyze this data, offering prescriptive guidance. For example, a European vineyard tool optimized fertilizer scheduling, reducing costs by 20% while maintaining grape quality [54]. DSS tools like Farm Logs and Climate Field View provide detailed advice on crop and soil conditions.

H. The Advantages of Wise Soil Use for The Environment

Smart systems improve soil fertility and environmental sustainability by minimizing chemical application, preventing water resource contamination, and managing nutrient levels. For example, potato farms in the Netherlands reduced their carbon footprint by 25% by adopting smart fertility practices [55]. Renewable energy technologies, such as solar-powered irrigation systems combined with AI, can further enhance aquaculture and post-harvest operations, ensuring sustainable agricultural practices [56]. These systems align productivity with ecological stewardship, promoting long-term soil health and reducing carbon footprint, while conserving inputs and reducing greenhouse emissions.

IV. CROP YIELD IMPROVEMENT WITH SMARTER AGRICULTURE

One of the most important factors that will raise the world's food demands with less of an impact on the environment and resource waste is crop yield. IoT, artificial intelligence, robots, and geospatial analytics are just a few of the technology innovations that smart farming systems incorporate into traditional farming methods. Farmers will benefit from automation, accurate management, and real-time monitoring to maximize crop health, efficiency, and yield potential. Some of the areas where smart systems increase crop productivity are listed below:

A. Precision Agriculture

Precision agriculture is a key component of smart farming, enabling the precise and efficient application of inputs like seeds, fertilizer, and water. It transforms traditional farming practices into data-driven systems, reducing waste and improving productivity. Variable rate seeding ensures ideal planting density for specific field zones, minimizing crop competition and maximizing germination [57]. Fertilizer optimization minimizes excess application and prevents environmental harm. Targeted irrigation, powered by advanced systems and soil moisture sensors, provides accurate watering tailored to plant needs. For example, in the United States, a corn farmer using variable rate technology reported a 15% increase in yield while reducing fertilizer use by 20% [58]. Economically, precision agriculture reduces input costs while increasing output, with studies showing up to a 20% yield increase and a 15% reduction in input expenses. Use of solar powered aquaponic system [59] alongside farming improves the operational efficiency as well as sustainability.

B. Crop Monitoring in Meal Time

IoT-enabled devices, drones, and satellite imaging are used in real-time crop monitoring to identify early pressures from diseases, pests, ripening status and nutritional deficiencies. These technologies use multispectral imaging, which gathers data across multiple wavelengths, to reveal plant health differences that are invisible to the naked eye. IoT-based sensors provide real-time information on growth conditions, while AI-powered diagnostics analyze anomalies, predict disease outbreaks, and suggest corrective actions. For example, in India, tea plantations use drones equipped with multispectral cameras to monitor pest infestations, reducing chemical use by 25% [60]. The integration of cost-effective tools for small-scale farmers could enhance accessibility and broaden adoption of these technologies [61]. **Fig.3**, illustrates the integration of IoT devices, drones, and satellite imaging for effective real-time crop monitoring.

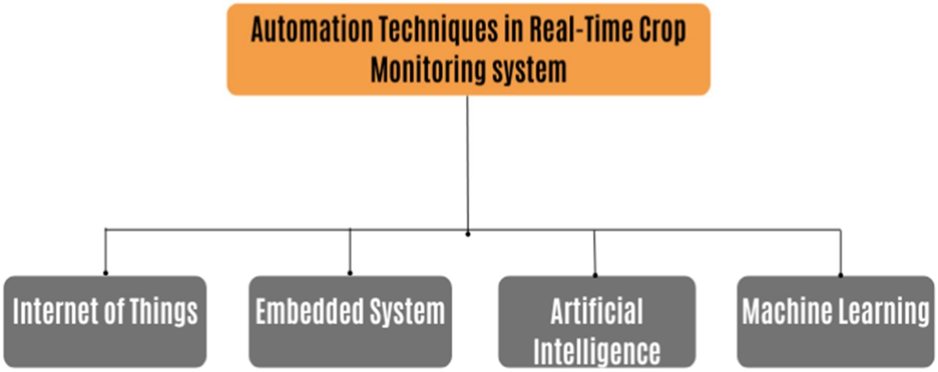

Fig. 3 Technology in real time crop monitoring system

C. Advanced Management of Irrigation

Smart irrigation is crucial for efficient water use in drought-prone regions. It uses IoT sensors to deliver water directly to the root zone, minimizing evaporation and runoff. Weather-integrated systems use soil moisture data and weather forecasts to optimize irrigation schedules. Automated sprinklers use real-time sensor data to adjust watering schedules. For example, farmers in Israel have implemented smart drip irrigation systems, reducing water consumption by 40% and increasing crop yields [62]. These practices conserve water, reduce resource wastage, and create ideal growth conditions for crops. Overall, advanced irrigation management is essential for ensuring water-efficient agricultural practices.

D. Pest and Disease Management

Smart pest and disease management uses advanced detection, prediction, and control technologies to minimize yield losses and reduce chemical pesticide use. Remote sensing via drones captures high-resolution images, identifying early signs of disease or pest activity [63]. IoT traps monitor pest populations and send alerts when intervention thresholds are reached. Precision spraying by drones applies pesticides only to affected areas, conserving chemicals [64], [65]. Biological controls integrate natural agents into smart systems for sustainable pest management. For example, in Pakistan, AI-powered systems predict fungal infections, reducing losses by 30% [66]. Cost comparisons between traditional and smart pest management methods can demonstrate the economic benefits of these technologies.

E. Crop Forecasting and Managing Yield

Farmers may maximize harvest timing for optimal storage and market planning with accurate yield estimation. Yields could be accurately estimated in the past when real-time data was input into intelligent systems. Machine learning algorithms forecast crop production by utilizing historical data, meteorological conditions, and soil health metrics [67]. With the use of multiple vegetation indices, most notably the Normalized Difference Vegetation Index, it facilitates remote spatial yield prediction. Stem diameter and leaf area index are evaluated by on-farm sensors to estimate yield. In Australia, wheat farmers using yield prediction tools have optimized harvest schedules and reduced post-harvest losses by 15% [68]. Advantages improved preparation for the requirement for machinery and labor. Reduce post-harvest losses by using the best possible transportation and storage improved supply projections and market strategy.

F. Robotics and Autonomous Machinery

Automation in farm operations is reshaping the way farmers work. Robotics and autonomous machinery are automating tasks like picking fruits and vegetables, weeding, and tilling, reducing labor dependency and improving efficiency. For example, strawberry farms in California have seen an increase in picking efficiency, saving time and reducing labor costs by 20% [69]. These systems also offer more accuracy and reduce the need for physical labor. Examples include the Harvey Robot, which automates fruit and vegetable picking with minimal human labor, and the weeding robot, which uses AI to distinguish between crops and weeds, then mechanically eradicate them or target them with herbicides [70]. Application of automation techniques in food processing machinery encourages superior production and processing quality [71].

G. Climate-Aware Solutions

Climate-aware solutions are transforming agriculture by reducing risks and increasing resilience. These include drought-resilient farming, biogenic nanoparticle use for organic farming [72], which selects crops that thrive with limited water supplies, and frost management systems that send alerts to enable pre-spray of anti-frost agents or crop coverings. Canadian apple orchards use frost detection systems to prevent losses during unexpected frost events, saving up to $50,000 annually per farm [73]. These technologies improve productivity even under adverse weather conditions and minimize financial losses caused by climate-related crop failures. Climate-resilient practices provide appropriate cultivars and assess how various crops will change if conditions change. Drought-resilient farming chooses crops that thrive with limited water sources while maximizing water use [74]. Smart weather stations send frost alarms, enabling farmers to pre-spray anti-frost agents or cover crops. **Table 2**, summarizes the effects of climate change on plant pests, including shifts in geographical distribution and lifecycle patterns.

Table 2. The effects of climate change on plant pests.

Pest species	Region	Changes	References
European spruce bark beetle (*Istypographies Linnaeus*)	Norway	Two generations are recorded in forests instead of one generation per year due to warming.	[75]
Old world bollworm (*Helicoverpa armigera Hübner*)	United Kingdom and the northern edge of its range in Europe	Extension of geographical distribution from 1969 to 2004.	[76]
Oak processionary moth (*Thaumetopoea processionea Linnaeus*)	Central and Southern Europe, Belgium, Netherland.	Geographical region extension: from Central and Southern Europe to Belgium, Netherlands, and Denmark.	[76]
Nun moth (*Lymantria monacha Linnaeus*) and the gypsy moth *(Lymantria dispar Linnaeus*)	Europe	Extension of the northward shift distribution range (approximately500–700 km) and retraction of the southern edge ranges by 100–900 km.	[77]
Wheat yellow rust (*Puccinia striiformis Westend)*	Northern Indian state of Punjab	Emergence of a new pathotype which can cause infection in late December due to higher temperatures	[78]
Phytophthora infestans	Northern Indian state of Punjab	Local thermal adaptation with invasive behavior linked to increase aggressiveness	[79]

H. Supply Chain Incorporation

Smart systems in agriculture are improving supply chain efficiency and reducing post-harvest losses. IoT-enabled warehousing maintains optimal temperature and moisture conditions, while online market platforms connect farmers with consumers. Blockchain technology can enhance transparency and traceability, ensuring consumer trust and compliance with quality [80]. Colombian coffee producers use blockchain to verify fair trade practices, increasing consumer confidence and securing premium prices.

V. CHALLENGES AND LIMITATIONS

Smart agricultural technologies, which have the potential to advance farming techniques, encounter several challenges. High installation costs, the requirement for modern technologies such as IoT, AI, and robots, and the difficulty of handling the massive volumes of data created by these systems all pose substantial challenges [81]. Connectivity concerns, especially in rural regions with limited internet connectivity, impede the real-time operation of IoT devices and cloud-based applications [82]. Integrating smart systems with legacy equipment is particularly challenging, as most old farming machinery is incompatible with current technologies. Farmers' lack of technical expertise and training leads to a high learning curve and discourages adoption [83]. Farmers are also concerned about the ownership and potential abuse of sensitive information, which adds to their uncertainty. Addressing these challenges is crucial to unlocking the full potential of smart agricultural technologies for sustainable and efficient farming.

VI. PROSPECTS FOR THE FUTURE

With the speed at which technology is developing, this section demonstrates the enormous potential of smart systems to entirely reshape agriculture. The future of farming lies in the greater integration of technologies like AI, machine learning, IoT, and data analytics, which promise to improve agricultural yield, soil health, and sustainability. There are several future prospects:

1) *Enhanced AI and ML capabilities:* AI and ML are expected to play a more prominent role in automating decision-making and improving predictive capabilities [84]. These advancements will enable farmers to anticipate weather changes, pest outbreaks, and crop health issues with greater accuracy, ensuring proactive and effective responses.
2) *Data integration and advanced analytics:* The integration of diverse data sources, including weather forecasts, soil sensors, and crop health data, will provide a more holistic view of farm operations. Cloud computing and advanced analytics will allow for more precise and comprehensive farm management strategies [85].
3) *Sustainability and regenerative agriculture:* Smart systems will support regenerative agricultural practices by analyzing soil health, optimizing resource use, and reducing environmental impact. Technologies like AI and IoT will help implement advanced pest management techniques and promote soil conservation, contributing to sustainable farming systems [86].
4) *Improved accessibility and affordability:* As technology becomes more affordable and accessible, even small-scale farmers will benefit from smart farming solutions [87]. Efforts to bridge the digital divide and provide training will further democratize the adoption of these systems.
5) *Climate-resilient farming:* Smart systems will enhance resilience to climate change by providing tools to mitigate risks such as droughts, frost, and erratic weather patterns [88]. Farmers will be able to select climate-appropriate crops and adopt adaptive farming practices to safeguard productivity.
6) *Vision for the future:* Smart farming systems are poised to shape the agriculture of tomorrow by achieving the dual goals of increased productivity and environmental sustainability [89]. 3D printing applications in smart farming machinery design [90] as well as other smart sensors and innovative food items design [91] will enlighten the future of agricultural practices. These technologies will not only help meet the growing global demand for food but also reduce the strain on natural resources. By fostering innovation, collaboration, and responsible practices, smart systems will drive a more resilient, efficient, and sustainable agricultural industry.

VII. CONCLUSION

Smart technology in agriculture has significantly improved crop yield by enhancing efficiency and precision while ensuring sustainability. Utilizing cutting-edge technologies like robotics, artificial intelligence, the Internet of Things, and GIS tools, these systems optimize all aspects of the agricultural process, allowing farmers to input precise inputs and make data-driven decisions. This not only increases yield but also conserves resources like water, fertilizer, and pesticides, benefiting the environment and economy. Smart technology also increases resilience by providing tools for responding to climate variability and reducing risks of drought, erratic weather, and insect outbreaks.

Robotics and autonomous equipment reduce human labor, making farming operations more effective and scalable. Climate-smart solutions and yield prediction algorithms provide farmers with insights to improve planning and productivity. However, widespread adoption is hindered by implementation costs, technical expertise, and infrastructure accessibility in remote areas. As technology becomes more accessible and affordable, smart systems will become more integrated into the farming industry, ensuring environmental sustainability and high output.

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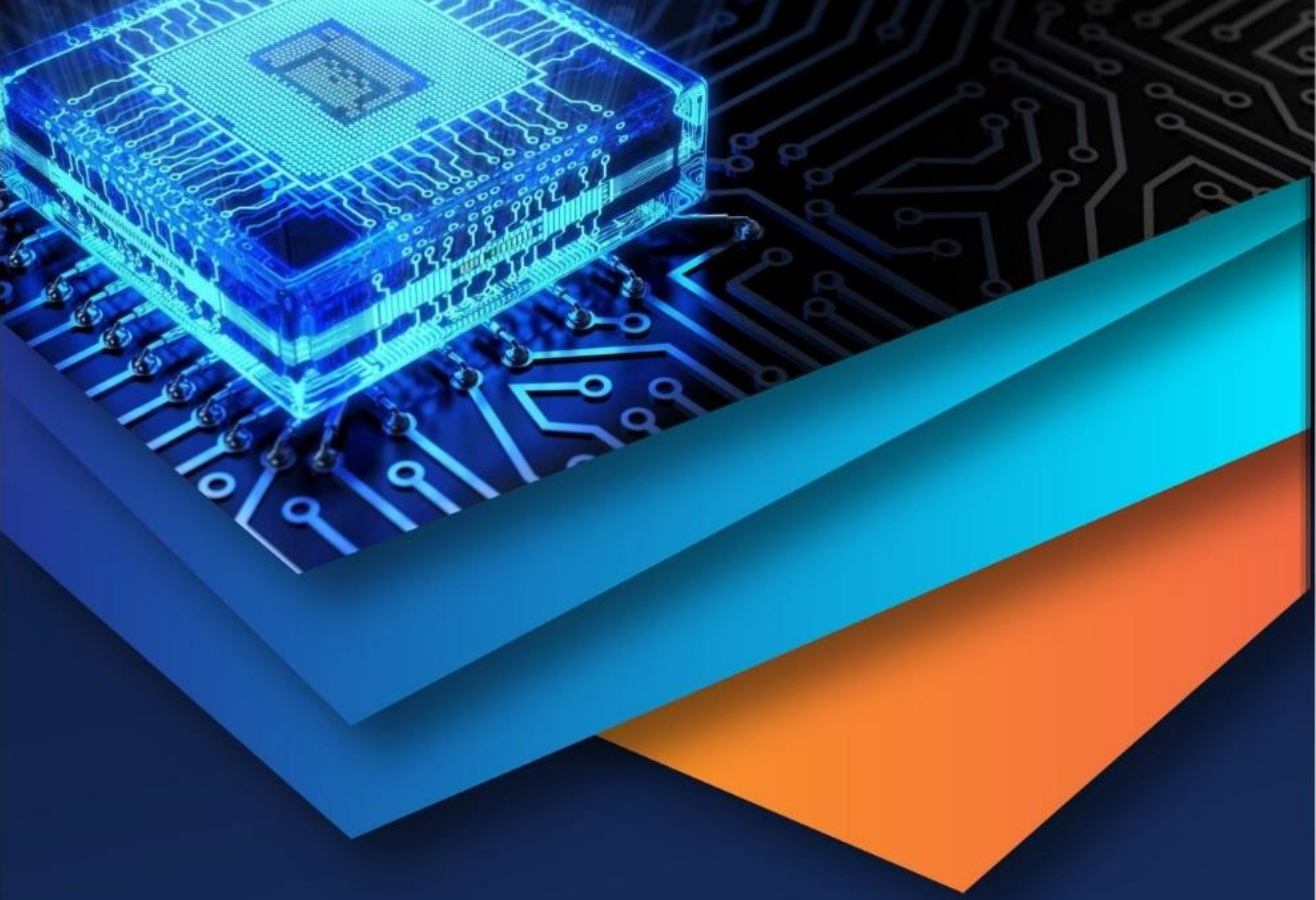

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