Transforming Agriculture: Harnessing Robotics and Drones for Sustainable Farming Solution

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Review Article

ABSTRACT

The agricultural sector is facing unprecedented challenges due to increasing food demand, environmental degradation, and labour shortages, exacerbated by a burgeoning global population. To address these issues sustainably, the concept of "smart farming" utilizing advanced robotics and drones has emerged as a transformative solution. This review paper delves into the significant impact of these cutting-edge technologies on modern agriculture, focusing on their applications, benefits, challenges, and future prospects. Robotics in agriculture have advanced considerably, playing crucial roles in tasks such as tillage, seeding, crop protection, harvesting, and animal husbandry. The latest robotic systems are equipped with artificial intelligence (AI) and machine learning algorithms, enabling them to perform complex tasks with high precision and efficiency. These technologies have the potential to enhance productivity while minimizing environmental impacts through precision farming techniques. Drones, similarly, have revolutionized precision agriculture with their applications in monitoring, spraying, mapping, and surveillance. The latest

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drone models are equipped with multispectral sensors, GPS technology, and AI-driven analytics, providing farmers with real-time data and actionable insights. This helps in optimizing resource use, improving crop health, and increasing yield while reducing environmental footprints. Despite these advancements, several challenges impede widespread adoption. High initial costs, technological learning curves, regulatory hurdles, and data security concerns remain significant barriers. Additionally, the integration of these technologies requires substantial infrastructure and training, which can be daunting for small-scale farmers. The paper emphasizes the need for strategic investments and supportive policies to overcome these challenges. Collaborations between technology developers, agricultural experts, and policymakers are crucial to drive innovation and facilitate the adoption of smart farming practices. Robotics and drones hold immense potential to revolutionize traditional farming practices. By harnessing these technologies, the agriculture industry can achieve sustainable solutions, enhancing productivity and ensuring food security for the future. This review provides a comprehensive analysis of the current state and future directions of smart farming, underscoring the pivotal role of robotics and drones in transforming agriculture.

1. INTRODUCTION

Agriculture, the primary source of food worldwide, faces a myriad of challenges exacerbated by the growing demand for food, food safety and security concerns, environmental preservation, water conservation, and the overarching goal of sustainability [1]. As the global population is projected to reach between 9 and 11 billion by 2050, the agriculture sector must navigate significant obstacles arising from these increased demands [2]. The concept of "smart farming," which leverages advanced technologies such as drones and robotics, emerges as a promising solution to sustainably address these issues [3]. The intensification of farming practices, along with the escalating use of fertilizers and pesticides, poses significant environmental risks. These practices can lead to soil degradation, water contamination, and loss of biodiversity, threatening the long-term viability of agricultural ecosystems. Additionally, the challenge is compounded by the decreasing availability of arable land and a declining number of farmers, both of which necessitate innovative and sustainable farming approaches to maintain productivity and ensure food security.

Smart farming, with a particular focus on drones and robotics, offers a strategic approach to mitigate these challenges by reducing reliance on human labour and optimizing agricultural processes [4]. The integration of machine learning and deep learning within AI applications has facilitated the development of autonomous machinery, such as tractors, harvesters, and robotic weeders [5-7]. These advancements are revolutionizing traditional farming practices by enhancing efficiency, minimizing errors, and providing more accurate yield predictions. As a result, farmers can achieve increased efficiency and substantial cost savings. Drones have become integral to precision agriculture, providing valuable applications in monitoring, spraying, mapping, and surveillance. Equipped with multispectral sensors, GPS technology, and AI-driven analytics, modern drones offer real-time data and actionable insights [8]. This enables farmers to optimize resource use, improve crop health, and increase yield while reducing environmental impacts. By delivering precise information on crop conditions, soil health, and pest infestations, drones allow for targeted interventions that reduce the need for broad-spectrum chemical applications, thereby fostering more environmentally friendly practices.

The adoption of precision agriculture technologies in field operations also contributes significantly to reducing greenhouse gas emissions. By managing inputs more effectively, enhancing fuel efficiency, and promoting carbon sequestration, these technologies help mitigate the agricultural sector's environmental footprint [9]. Encouraging the adoption of environmentally friendly practices and reducing chemical usage not only supports a healthier ecosystem but also aligns with global sustainability goals. Despite the numerous benefits, several challenges impede the widespread adoption of these technologies. High initial costs, technological learning curves, regulatory hurdles, and data security concerns remain significant barriers. Furthermore, the integration of these advanced technologies requires substantial infrastructure and training, which can be particularly daunting for small-scale farmers. Addressing these challenges necessitates strategic investments

and supportive policies to facilitate the adoption of smart farming practices.

Collaborations between technology developers, agricultural experts, and policymakers are crucial to drive innovation and ensure that the benefits of smart farming are accessible to all farmers, regardless of scale. Such partnerships can help overcome financial and technical barriers, providing the necessary resources and knowledge to implement these advanced technologies effectively [10]. In conclusion, the integration of drones and robotics in agriculture holds immense potential to revolutionize traditional farming practices. By harnessing these technologies, the agriculture industry can achieve sustainable solutions that enhance productivity, ensure food security, and reduce environmental impacts. This review provides a comprehensive analysis of the current state and future directions of smart farming, underscoring the pivotal role of robotics and drones in transforming agriculture for a sustainable future.

2. USE OF ROBOTS IN SUSTAINABLE AGRICULTURE

Agricultural robots, also known as agribots, represent a specialized category within the broader realm of robotics, designed specifically for farming purposes [11]. These robots are equipped with advanced capabilities in perception, decision-making, and execution, enabling them to operate effectively in challenging and hazardous agricultural environments. With the increasing demand for labour-saving techniques and efficient agricultural production, the development of agricultural robots has continuously evolved to cater to diverse application scenarios. Depending on their intended tasks, agricultural robots encompass various types tailored for specific agricultural activities, such as handling fruits and vegetables and managing livestock. Robots play a crucial role in sustainable agriculture by performing tasks that enhance efficiency and reduce the environmental impact of farming operations [12]. For instance, robotic systems are now capable of precision tillage, seeding, and weeding, which minimize soil disturbance and reduce the need for chemical herbicides. Harvesting robots, designed to handle delicate fruits and vegetables, help in reducing crop wastage and labour costs. In livestock management, robots assist in feeding, milking, and monitoring animal health, ensuring better animal welfare and productivity [13]. These advancements not only increase operational efficiency but also promote sustainable farming practices by conserving resources and minimizing negative environmental impacts. Fig. 1 depicts a few examples of field applications, including fertilization robots, irrigation robots, weeding robots, and picking robots.

Fig. 1. Different uses of robots in Dryland, field, orchards and greenhouses [14]

Despite the numerous benefits, several challenges impede the widespread adoption of these technologies. High initial costs, technological learning curves, regulatory hurdles, and data security concerns remain significant barriers. Furthermore, the integration of these advanced technologies requires substantial infrastructure and training, which can be particularly daunting for small-scale farmers. Addressing these challenges necessitates strategic investments and supportive policies to facilitate the adoption of smart farming practices. Collaborations between technology developers, agricultural experts, and policymakers are crucial to drive innovation and ensure that the benefits of smart farming are accessible to all farmers, regardless of scale [15]. Such partnerships can help overcome financial and technical barriers, providing the necessary resources and knowledge to implement these advanced technologies effectively.

In conclusion, the integration of drones and robotics in agriculture holds immense potential to revolutionize traditional farming practices. By harnessing these technologies, the agriculture industry can achieve sustainable solutions that enhance productivity, ensure food security, and reduce environmental impacts. This review provides a comprehensive analysis of the current state and future directions of smart farming, underscoring the pivotal role of robotics and drones in transforming agriculture for a sustainable future.

2.1 Terrestrial Robots

Terrestrial robots, primarily operating on the ground, are autonomous or semi-autonomous machines designed to perform a variety of agricultural tasks [16]. These robots are equipped to handle soil preparation, seed planting, crop care, data collection, and harvesting. Some advanced models can even perform aerial tasks like crop spraying. The deployment of these robots is transforming traditional farming practices by enhancing efficiency, reducing labor requirements, and promoting sustainability. Among the various types of terrestrial robots, tillage robots, seeding robots, crop protection robots, field information collection robots, and harvesting robots play crucial roles [17].

Tillage Robots: Tillage robots represent a significant advancement in land preparation, reducing farmers' workload while improving cultivation quality and speed. These autonomous or semi-autonomous machines utilize advanced software to seamlessly integrate hardware and software tools, ensuring precise tillage operations. Panarin's development of tillage robot software exemplifies this integration, enhancing soil health and preparing the land effectively for planting [18].

Seeding Robots: Automated seeding robots play a crucial role in optimizing planting processes, leading to cost savings and efficiency improvements. IoT-controlled seed-sowing robot achieves complete seeding automation, ensuring uniform seed distribution and optimal planting depth [19]. By reducing the need for manual labor, these robots promote sustainability in farming while enhancing planting efficiency and crop yield potential.

Crop Protection Robots: Intelligent robotic systems for crop protection minimize human exposure to harmful pesticides, employing high-efficiency trajectory algorithms for precise spraying. The development of robotic systems that efficiently manage pesticide application, reducing environmental impact while ensuring effective pest control [20]. These robots contribute to sustainable farming practices by minimizing chemical usage and promoting environmentally friendly pest management techniques.

Field Information Collection Robots: Equipped for field data collection, these robots assist farmers in decision-making by gathering essential agricultural insights. The University of Saskatchewan's development of mobile robotic platforms for monitoring crop health, such as their Canola plant phenotyping robot, exemplifies the potential of these technologies to provide valuable insights into crop conditions and soil health [21]. By enabling informed decision-making, these robots enhance farming practices and promote sustainability in agriculture.

Harvesting Robots: Automated harvesting robots streamline the harvesting process, significantly improving efficiency and reducing labour costs. Development of an automatic corn harvester system with a high success rate exemplifies the potential of these robots to address the need for efficient and timely harvesting solutions [22]. By minimizing crop wastage and labour requirements, harvesting robots contribute to the overall sustainability of

farming operations while enhancing productivity and profitability.

2.2 Horticultural Robots

In response to labour shortages, horticultural robots are transforming farming practices for fruits and vegetables, offering innovative solutions to enhance efficiency and productivity. These robots encompass various functionalities including transplanting, patrolling, pesticide spraying, gardening, and picking, each tailored to address specific challenges in horticultural operations [23].

Transplanting Robots: Precision transplanting robots play a crucial role in ensuring accuracy and stability during crop transplantation, thereby optimizing planting efficiency. Ongoing research aims to improve transplanting control and success rates, with a focus on optimizing crop establishment and growth.

Patrol Robots: Independent patrolling robots gather essential information on crop maturity, pests, and environmental conditions, providing farmers with valuable insights for decision-making processes. These robots enhance monitoring capabilities and enable timely interventions to maintain crop health and productivity.

Pesticide Spraying Robots: Pesticide spraying robots employ various methods for precise and efficient pesticide application, reducing environmental impact while ensuring effective pest control. Advanced spraying techniques are explored to minimize chemical usage and promote sustainable pest management practices.

Gardening Robots: Autonomous gardening robots navigate dynamically changing garden environments, with a focus on improving navigation and adaptability to seasonal changes. Research efforts aim to enhance robot mobility and performance in diverse gardening settings, ensuring efficient and effective management of horticultural crops.

Picking Robots: Fruit and vegetable picking robots facilitate large-scale harvesting with selective or bulk picking capabilities, addressing labor shortages in agricultural settings. These robots are designed to improve efficiency and reduce labor costs, ensuring timely and cost-effective harvesting of horticultural crops.

2.3 Animal Husbandry Robots

Optimizing livestock production through smart automation is crucial for addressing long-term challenges in animal husbandry [24]. These robots encompass various functionalities including breeding, feed dispensing, milking, and egg collection, each contributing to improved productivity, hygiene, and welfare in animal farming operations.

Breeding Robots: Disinfection robots and automated breeding systems play a vital role in enhancing livestock productivity and hygiene, reducing disease risks, and improving production efficiency [25]. By automating breeding processes, these robots ensure optimal conditions for successful reproduction, contributing to overall herd health and genetic diversity.

Feed Dispensing Robots: Automated feeding systems for livestock minimize feed waste and labor costs, enhancing production efficiency and promoting animal welfare. By precisely dispensing feed according to individual nutritional requirements, these robots optimize feed utilization and ensure consistent access to nutrition, thereby improving animal growth and performance.

Milking Robots: Automatic milking systems revolutionize dairy farming by enabling continuous milking operations and data-driven farm management. These robots automate the milking process, ensuring efficient milk extraction while monitoring milk quality and cow health in real-time [26]. By streamlining milking operations, these systems increase milk yield and profitability while reducing labor requirements.

Egg Collection Robots: Mobile robots for egg collection streamline poultry house operations, improving efficiency and minimizing manual labor. These robots navigate poultry houses autonomously, collecting eggs efficiently and ensuring timely removal from the production environment. By reducing the reliance on manual labor, these robots enhance productivity and hygiene in egg production facilities.

Overall, the development and adoption of agricultural robots offer significant potential for optimizing farming practices, enhancing productivity, and mitigating labor challenges across diverse agricultural domains. These robots represent a transformative solution for

sustainable livestock production, contributing to improved animal welfare, environmental stewardship, and economic viability in animal husbandry operations.

3. TYPES OF ROBOTS USED IN SUSTAINABLE AGRICULTURE

3.1 Terrestrial Robots

Terrestrial robots, also known as agribots, are ground-based machines designed for various agricultural tasks. These robots are equipped with advanced capabilities for tasks such as soil preparation, seeding, weeding, and harvesting. They contribute to sustainable agriculture by reducing the reliance on manual labor, minimizing the use of agrochemicals, and optimizing resource management.

3.2 Aerial Drones

Aerial drones, also referred to as UAVs (Unmanned Aerial Vehicles), play a crucial role in sustainable agriculture by providing aerial imagery, mapping, and monitoring capabilities [27]. These drones can assess crop health, detect pest infestations, and monitor soil moisture levels, enabling farmers to make data-driven decisions. Aerial drones help optimize resource allocation, reduce environmental impact, and improve crop yields in sustainable farming practices.

3.3 Robotic Harvesters

Robotic harvesters automate the process of crop harvesting, offering efficiency and precision in sustainable agriculture. These robots are designed to harvest crops such as fruits, vegetables, and grains with minimal damage to the produce. By reducing the need for manual labor and optimizing harvesting techniques, robotic harvesters contribute to labor efficiency, reduce post-harvest losses, and promote sustainable agricultural practices [28].

3.4 Autonomous Tractors

Autonomous tractors are self-driving vehicles equipped with advanced navigation and control systems for various farm operations. These tractors can perform tasks such as ploughing, seeding, and spraying with precision and efficiency. By optimizing field operations, reducing fuel consumption, and minimizing soil compaction, autonomous tractors support sustainable agriculture practices that prioritize resource conservation and environmental stewardship.

4. TYPES OF ROBOTS IN SUSTAINABLE AGRICULTURE

4.1 Multirotor Drones

Multirotor drones, characterized by multiple rotors arranged symmetrically, are pivotal in sustainable agriculture for their versatility. They excel in tasks like crop monitoring, aerial mapping, and precision spraying, providing detailed insights into crop health and soil conditions [29]. With the capability to hover and navigate closely over fields, these drones offer real-time data, empowering farmers to make informed decisions for optimized yields and reduced environmental impact.

4.2 Fixed-Wing Drones

Fixed-wing drones, resembling traditional aircraft with rigid wings, are prized for their endurance and extensive coverage in sustainable agriculture. Ideal for large-scale mapping, surveying, and crop scouting, they efficiently monitor soil erosion, vegetation health, and land management practices. Their contribution supports sustainable land use planning and conservation efforts by providing comprehensive data over expansive agricultural landscapes.

4.3 Hybrid VTOL Drones

Hybrid Vertical Takeoff and Landing (VTOL) drones blend fixed-wing stability with rotor-based agility, making them adaptable tools in sustainable agriculture [30]. Featuring propellers on fixed wings, these drones enable vertical takeoff and landing along with forward flight. They are utilized for crop surveillance, aerial imaging, and precision agriculture, ensuring efficiency across varied terrain types and enhancing agricultural practices.

4.4 Target and Decoy Drones

Target and decoy drones serve specialized roles in sustainable agriculture by mimicking threats such as pests or birds. Integrated into pest management strategies, these drones deter wildlife from crops, minimizing crop damage and reducing the need for chemical interventions.

Their strategic deployment aids in mitigating losses while promoting eco-friendly pest control practices, aligning with sustainability goals in agriculture.

5. DRONES IN SUSTAINABLE AGRICULTURE

Drones have become integral to sustainable agriculture, revolutionizing traditional farming practices with their advanced capabilities. The concept of drones took nearly half a century to materialize into agricultural applications, with Yamaha unveiling the R-50 in 2000 [31]. This pioneering agricultural drone marked a significant shift in farming technology, enabling tasks like crop mapping and field analysis with unprecedented precision. Commonly known as Unmanned Aerial Vehicles (UAVs) or Unmanned Aircraft Systems (UAS), drones offer numerous advantages over traditional remote-sensing methods. They excel in capturing high-resolution images, even in challenging weather conditions, and provide cost-efficient alternatives to manned aircraft for aerial data collection. With their simplicity in setup and maintenance, drones have become indispensable tools for various applications beyond agriculture, including supply chain management, surveying, disaster management, and wildlife conservation. Initially developed for military purposes, drones have seamlessly transitioned into civilian domains, offering a wide range of benefits across industries. In agriculture, they facilitate smart farming practices by providing real-time data on crop health, soil conditions, and pest infestations, enabling farmers to make informed decisions and optimize resource management [32]. As technology continues to advance, drones are poised to play an increasingly pivotal role in promoting sustainability and efficiency in agricultural operations.

6. USES OF DRONES

Drones, with their integration of computing capabilities, advanced technologies, and on-board sensors, have found myriad applications in agriculture. They provide valuable assistance in farming by swiftly delivering essential information for making decisions regarding irrigation, fertilization, and pest management. Precision spraying is a critical function drones excel in, effectively reducing chemical wastage and enhancing resource optimization [33]. Fig. 2 illustrated Various uses of drones in agricultural practices. Moreover, they are indispensable tools for mapping and surveying agricultural landscapes, facilitating informed crop planning and resource distribution. Additionally, drones play a vital role in monitoring plant health, managing weed growth, and executing spraying tasks in agricultural settings. Their diverse applications span crop monitoring, soil and field analysis, and bird control, all contributing to the advancement of precision and sustainable agriculture practices. In sum, drones have the potential to revolutionize agriculture by significantly improving efficiency, productivity, and sustainability.
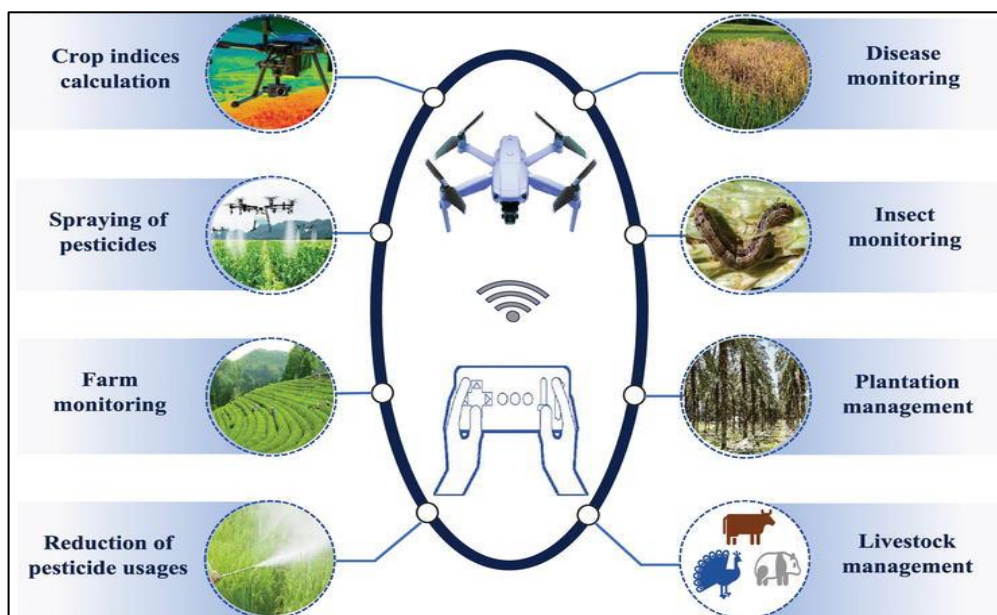

Fig. 2. Various uses of drones in agricultural practices

Drones are increasingly being utilized in sustainable agriculture for tasks such as precision farming, environmental monitoring, and crop surveillance. With their ability to capture high-resolution aerial imagery and data, drones aid farmers in optimizing resource allocation, reducing input wastage, and minimizing environmental impact [34]. They enable targeted interventions, such as precision spraying and irrigation, resulting in improved crop yields and reduced water and chemical usage. Furthermore, drones contribute to the implementation of agroecological practices by providing real-time insights into soil health, crop conditions, and pest infestations. By facilitating timely interventions and proactive management strategies, drones support sustainable farming methods that prioritize biodiversity conservation and ecosystem health. Additionally, drones assist in climate resilience efforts by monitoring weather patterns, assessing crop vulnerability to climate change, and facilitating adaptive management practices to mitigate risks and ensure food security in a changing climate [35].

7. THE FUTURE OF DRONES AND ROBOTS IN SUSTAINABLE AGRICULTURE

In the ever-evolving landscape of agriculture, drones and robots stand at the forefront of innovation, offering transformative solutions to enhance sustainability, productivity, and efficiency. As technological advancements continue to accelerate, the future of sustainable agriculture is intricately intertwined with the evolution and integration of these unmanned systems. With their ability to perform a diverse range of tasks, from precision farming to environmental monitoring, drones and robots hold immense potential to revolutionize the way we cultivate food and manage natural resources [36].

7.1 Heading into the Future: Advancements in Drone Technology

Drones, also known as Unmanned Aerial Vehicles (UAVs), are poised to play a central role in the future of sustainable agriculture. With ongoing advancements in drone technology, we can expect to see a proliferation of specialized drones tailored to meet the unique needs of farmers and agricultural landscapes [37]. These drones will be equipped with advanced sensors, imaging technologies, and artificial intelligence algorithms, enabling them to provide real-time data and insights for precision agriculture practices. From monitoring crop health and detecting pest infestations to optimizing irrigation and fertilizer application, drones will become indispensable tools in the farmer's toolkit, driving efficiency and sustainability across the agricultural value chain.

7.2 Heading into the Future: Robotic Revolution in Farming

In parallel, robotics in agriculture is poised for a revolution, with autonomous robots set to transform traditional farming practices. Future robots will be capable of performing a wide range of tasks with precision and efficiency, including planting, weeding, harvesting, and post-harvest handling. These robots will be equipped with advanced sensors, actuators, and machine learning algorithms, enabling them to navigate complex agricultural environments, identify and respond to crop variability, and minimize resource wastage [38]. By automating labour-intensive tasks and optimizing resource management, robotic systems will empower farmers to achieve higher yields, lower costs, and reduced environmental impact, thereby advancing the principles of sustainable agriculture.

7.3 The Future Landscape: Integration and Collaboration

Looking ahead, the future of sustainable agriculture will be characterized by the seamless integration and collaboration between drones, robots, and traditional farming practices. Farmers will leverage these technologies as part of holistic farming systems, combining data-driven insights with agronomic expertise to make informed decisions and optimize resource allocation [39]. Collaborative efforts between industry stakeholders, researchers, policymakers, and farmers will drive innovation and accelerate the adoption of drone and robotic technologies in agriculture. Furthermore, investments in infrastructure, training, and regulatory frameworks will be crucial to overcoming barriers and ensuring

widespread adoption of these transformative technologies.

In conclusion, the future of drones and robots in sustainable agriculture holds immense promise for addressing the pressing challenges facing the global food system. By harnessing the power of unmanned systems, farmers can achieve greater efficiency, productivity, and sustainability in food production. As we navigate towards a more sustainable future, collaboration, innovation, and investment will be key drivers in realizing the full potential of drones and robots in agriculture, ultimately leading to a more resilient, equitable, and environmentally sustainable food system for generations to come.

8. BENEFITS AND CHALLENGES OF ADOPTING ROBOTICS AND DRONES IN AGRICULTURE

As agriculture transitions towards a more technologically advanced landscape, the adoption of robotics and drones offers a plethora of benefits and presents its fair share of challenges. These innovative technologies have the potential to revolutionize farming practices, but their integration into agricultural workflows requires careful consideration of various factors.

8.1 Benefits of Adopting Robotics and Drones

One of the primary benefits of adopting robotics and drones in agriculture is increased efficiency and productivity. These technologies enable automation of labour-intensive tasks such as planting, weeding, and harvesting, reducing the reliance on manual labor and optimizing resource utilization. For instance, robotic harvesters equipped with advanced sensors and actuators can precisely identify ripe crops and harvest them with minimal damage, leading to higher yields and improved crop quality [40]. Moreover, robotics and drones facilitate precision agriculture practices by providing real-time data and insights into crop health, soil conditions, and environmental factors. Drones equipped with high-resolution cameras and multispectral sensors can capture aerial imagery of fields, allowing farmers to monitor crop growth, detect pest infestations, and assess irrigation needs with unparalleled accuracy. This data-driven approach enables targeted interventions, such as variable-rate spraying and irrigation, leading to optimized inputs and reduced environmental impact [41]. Additionally, robotics and drones enhance safety and reduce risks associated with traditional farming practices. By automating hazardous tasks such as pesticide application and working in challenging terrain, these technologies minimize the exposure of farmers to harmful chemicals and accidents. Furthermore, drones can survey inaccessible or dangerous areas, providing valuable insights without putting human lives at risk.

8.2 Challenges of Adopting Robotics and Drones

Despite their numerous benefits, the adoption of robotics and drones in agriculture also presents several challenges that need to be addressed. One of the primary challenges is the high initial investment and operating costs associated with these technologies. The purchase and maintenance of robotics and drones require significant financial resources, which may pose barriers to adoption, especially for small-scale farmers with limited capital [42]. Moreover, there is a lack of standardized protocols and regulations governing the use of robotics and drones in agriculture. Issues such as airspace regulations, data privacy concerns, and safety standards need to be addressed to ensure the responsible and ethical deployment of these technologies [43]. Additionally, the rapid pace of technological advancements can lead to compatibility issues and interoperability challenges between different systems and platforms, hindering seamless integration into existing agricultural workflows.

Furthermore, there are concerns regarding the displacement of labour and the potential impact on rural communities. The widespread adoption of robotics and drones may lead to job losses in the agricultural sector, particularly for manual labourers and farmworkers. Addressing these socio-economic implications requires thoughtful planning and investment in retraining and reskilling programs to ensure a smooth transition to a technologically driven agricultural workforce. In conclusion, while the adoption of robotics and drones in agriculture offers numerous benefits, including increased efficiency, productivity,

and safety, it also presents its fair share of challenges. Overcoming these challenges requires collaborative efforts between industry stakeholders, policymakers, and researchers to address issues such as cost, regulation, and socio-economic impact [44]. By leveraging the potential of robotics and drones while addressing their limitations, agriculture can embrace a more sustainable and technologically advanced future.

9. CONCLUSION

In the realm of agriculture, robotics emerges as a dynamic field aimed at amplifying the efficiency, productivity, and sustainability of farming and food production processes. By assuming roles such as crop and soil monitoring, predictive analytics, supply chain management, and harvesting, robotics offers profound potential to transform traditional agricultural practices. These technological advancements hold promise in revolutionizing farming methods, leading to improved yields, reduced resource wastage, and minimized environmental impact. However, alongside its considerable benefits, the integration of robotics in agriculture encounters several challenges and limitations that necessitate careful consideration. High development and maintenance costs, alongside the absence of standardized protocols and regulations, pose significant hurdles to the widespread adoption of robotic technologies in farming communities. Moreover, ethical and social implications, coupled with concerns regarding environmental sustainability, further complicate the seamless integration of robotics into agricultural workflows. Despite these obstacles, projections by the Association for Unmanned Vehicle Systems International (AUVSI) underscore a notable uptick in the adoption of unmanned aerial vehicles (UAVs) for agricultural applications. It is estimated that by 2020, over 2900 UAVs will be deployed by more than 900 companies worldwide, signalling a growing interest and investment in agricultural robotics. Overcoming barriers such as high initial costs and policy reforms becomes imperative to democratizing access to robotic technologies and making them more accessible and farmer-friendly. Nevertheless, the rapid expansion of these innovative tools and technologies in agriculture holds promise for providing valuable insights and information to farmers. By enabling more informed decision-making and offering precise interventions, robotics in agriculture contributes to enhanced agricultural outcomes and fosters a more sustainable future for food production. Through strategic investments, collaborative efforts, and technological advancements, the potential of robotics in agriculture can be harnessed to address pressing challenges and drive positive change across the agricultural landscape.'

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Mc Carthy U, Uysal I, Badia-Melis R, Mercier S, O'Donnell C, Ktenioudaki A. Global food security–Issues, challenges and technological solutions. Trends in Food Science & Technology. 2018 Jul 1; 77:11-20.
2. Serraj R, Krishnan L, Pingali P. Agriculture and food systems to 2050: a synthesis. Agriculture & Food Systems to. 2019;2050:3-45.
3. Sharma V, Tripathi AK, Mittal H. Technological revolutions in smart farming: Current trends, challenges & future directions. Computers and Electronics in Agriculture. 2022;201: 107217.
4. Karunathilake EM, Le AT, Heo S, Chung YS, Mansoor S. The path to smart farming: Innovations and opportunities in precision agriculture. Agriculture. 2023; 13(8):1593.
5. Halder, Shuvadeep, Shampa Purkaystha, Tushar Ghosh, Subhash Chandra Ghosh, and Abid Hayat. application of precision farming in horticulture: a comprehensive review. Journal of Scientific Research and Reports 202430 (6):653-65.
Available:https://doi.org/10.9734/jsrr/2024/v30i62083.

6. Mondal Pinaki, Basu M, PBS. Bhadoria critical review of precision agriculture technologies and its scope of adoption in India. Journal of Experimental Agriculture International. 2011;1(3):49-68. Available:https://doi.org/10.9734/AJEA/2011/155.

7. Balafoutis AT, Beck B, Fountas S, Tsiropoulos Z, Vangeyte J, van der Wal T, Soto-Embodas I, Gómez-Barbero M, Pedersen SM. Smart farming technologies–description, taxonomy and economic impact. Precision agriculture: Technology and economic perspectives. 2017;21-77.

8. El Alaoui M, Amraoui KE, Masmoudi L, Ettouhami A, Rouchdi M. Unleashing the potential of IoT, Artificial Intelligence, and UAVs in contemporary agriculture: A comprehensive review. Journal of Terramechanics. 2024;115:100986.

9. Balafoutis A, Beck B, Fountas S, Vangeyte J, Van der Wal T, Soto I, Gómez-Barbero M, Barnes A, Eory V. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability. 2017;9(8): 1339.

10. Carayannis EG, Popescu D, Sipp C, Stewart M. Technological learning for entrepreneurial development (TL4ED) in the knowledge economy (KE): Case studies and lessons learned. Technovation. 2006;26(4):419-43.

11. Pradhan NC, Naik MA, Chowdhury M, Kushwah A, Asha KR, Dhar T, Gavhane KP, Urhe SB, Satpute AN. Robotic Seeding or Sowing System in Smart Agriculture. In Artificial Intelligence and Smart Agriculture: Technology and Applications. Singapore: Springer Nature Singapore. 2024 Mar 30;495-520.

12. Mahmud MS, Abidin MS, Emmanuel AA, Hasan HS. Robotics and automation in agriculture: present and future applications. Applications of Modelling and Simulation. 2020;4:130-40.

13. Melak A, Aseged T, Shitaw T. The Influence of Artificial Intelligence Technology on the Management of Livestock Farms. International Journal of Distributed Sensor Networks. 2024;(1): 8929748.

14. Shi J, Bai Y, Diao Z, Zhou J, Yao X, Zhang B. Row detection BASED navigation and guidance for agricultural robots and autonomous vehicles in row-crop fields: Methods and applications. Agronomy. 2023;13(7):1780.

15. Knierim A, Kernecker M, Erdle K, Kraus T, Borges F, Wurbs A. Smart farming technology innovations–Insights and reflections from the German Smart-AKIS hub. NJAS-Wageningen Journal of Life Sciences. 2019;90:100314.

16. Lytridis C, Kaburlasos VG, Pachidis T, Manios M, Vrochidou E, Kalampokas T, Chatzistamatis S. An overview of cooperative robotics in agriculture. Agronomy. 2021;11(9):1818.

17. Fountas S, Mylonas N, Malounas I, Rodias E, Hellmann Santos C, Pekkeriet E. Agricultural robotics for field operations. Sensors. 2020;20(9):2672.

18. Ditzler L, Driessen C. Automating agroecology: How to design a farming robot without a monocultural mindset? Journal of Agricultural and Environmental Ethics. 2022 Mar;35(1):2.

19. Rajesh PV, Ashvin J, Harish M, Kishore G, Nidheesh S. Fabrication of Equipment and IoT-Assisted Monitoring for Enhanced Zero-Till Farming. InEmerging Technologies and Marketing Strategies for Sustainable Agriculture. IGI Global. 2024;209-233.

20. Gonzalez-de-Santos P, Ribeiro A, Fernandez-Quintanilla C, Lopez-Granados F, Brandstoetter M, Tomic S, Pedrazzi S, Peruzzi A, Pajares G, Kaplanis G, Perez-Ruiz M. Fleets of robots for environmentally-safe pest control in agriculture. Precision Agriculture. 2017;18:574-614.

21. Ahmed N, Zhang B, Deng L, Bozdar B, Li J, Chachar S, Chachar Z, Jahan I, Talpur A, Gishkori MS, Hayat F. Advancing horizons in vegetable cultivation: a journey from ageold practices to high-tech greenhouse cultivation—A review. Frontiers in Plant Science. 2024;15: 1357153.

22. Oliveira LF, Moreira AP, Silva MF. Advances in agriculture robotics: A state-of-the-art review and challenges ahead. Robotics. 2021;10(2):52.

23. Krishna KR. Aerial robotics in agriculture: Parafoils, blimps, aerostats, and kites. Apple Academic Press; 2021 Apr 14.

24. Vlaicu PA, Gras MA, Untea AE, Lefter NA, Rotar MC. Advancing Livestock Technology: Intelligent Systemization for

Enhanced Productivity, Welfare, and Sustainability. AgriEngineering. 2024;6(2): 1479-96.

25. Zhang L, Guo W, Lv C, Guo M, Yang M, Fu Q, Liu X. Advancements in artificial intelligence technology for improving animal welfare: Current applications and research progress. Animal Research and One Health. 2024;2(1):93-109.

26. Hogenboom JA, Pellegrino L, Sandrucci A, Rosi V, D'Incecco P. Invited review: Hygienic quality, composition, and technological performance of raw milk obtained by robotic milking of cows. Journal of dairy science. 2019;102(9): 7640-54.

27. Raj R, Kar S, Nandan R, Jagarlapudi A. Precision agriculture and unmanned aerial Vehicles (UAVs). Unmanned aerial vehicle: Applications in agriculture and environment. 2020:7-23.

28. Kakarla US, Venkataramana A, Gopinath S, Shivaram K, Yugendhar K, Harika KV, Dixit S. Revolutionizing Agricultural Harvesting with IoT Application. InMATEC Web of Conferences. EDP Sciences. 2024;392:01014.

29. Peksa J, Mamchur D. A Review on the State of the Art in Copter Drones and Flight Control Systems. Sensors. 2024 Jan;24(11):3349.

30. Maddikunta PK, Hakak S, Alazab M, Bhattacharya S, Gadekallu TR, Khan WZ, Pham QV. Unmanned aerial vehicles in smart agriculture: Applications, requirements, and challenges. IEEE Sensors Journal. 2021 Jan 6;21(16): 17608-19.

31. Clarke R. Understanding the drone epidemic. Computer Law & Security Review. 2014 Jun 1;30(3):230-46.

32. Karunathilake EM, Le AT, Heo S, Chung YS, Mansoor S. The path to smart farming: Innovations and opportunities in precision agriculture. Agriculture. 2023; 13(8):1593.

33. Naqvi RZ, Farooq M, Naqvi SA, Siddiqui HA, Amin I, Asif M, Mansoor S. Big data analytics and advanced technologies for sustainable agriculture. Handbook of Smart Materials, Technologies, and Devices: Applications of Industry 4.0. 2020;1-27.

34. Nath S. A vision of precision agriculture: Balance between agricultural sustainability and environmental stewardship. Agronomy Journal. 2024 ;116(3):1126-43.

35. Balasundram SK, Shamshiri RR, Sridhara S, Rizan N. The role of digital agriculture in mitigating climate change and ensuring food security: an overview. Sustainability. 2023;15(6):5325.

36. Raj EF, Appadurai M, Athiappan K. Precision farming in modern agriculture. InSmart Agriculture Automation Using Advanced Technologies: Data Analytics and Machine Learning, Cloud Architecture, Automation and IoT. Singapore: Springer Singapore. 2022 Jan 1;61-87.

37. Mahadasa R, Surarapu P, Vadiyala VR, Baddam PR. Utilization of Agricultural Drones in Farming by Harnessing the Power of Aerial Intelligence. Malaysian Journal of Medical and Biological Research. 2020;7(2):135-44.

38. Oliveira LF, Moreira AP, Silva MF. Advances in agriculture robotics: A state-of-the-art review and challenges ahead. Robotics. 2021;10(2):52.

39. Jararweh Y, Fatima S, Jarrah M, AlZu'bi S. Smart and sustainable agriculture: Fundamentals, enabling technologies, and future directions. Computers and Electrical Engineering. 2023;110:108799.

40. Davidson J, Bhusal S, Mo C, Karkee M, Zhang Q. Robotic manipulation for specialty crop harvesting: A review of manipulator and end-effector technologies. Global Journal of Agricultural and Allied Sciences. 2020; 2(1):25-41.

41. Taseer A, Han X. Advancements in variable rate spraying for precise spray requirements in precision agriculture using Unmanned aerial spraying Systems: A review. Computers and Electronics in Agriculture. 2024;219:108841.

42. Costa F, Frecassetti S, Rossini M, Portioli-Staudacher A. Industry 4.0 digital technologies enhancing sustainability: Applications and barriers from the agricultural industry in an emerging economy. Journal of Cleaner Production. 2023;408:137208.

43. Finn RL, Wright D, Jacques L, De Hert P. Study on privacy, data protection and ethical risks in civil Remotely Piloted Aircraft Systems operations. Final Report, Luxembourg: Publications Office of the European Union. 2014 Feb;39.

44. Baker MR, Steins NA, Pastoors MA, Neuenfeldt S, de Boer A, Haasnoot D, Madsen S, Muller J, Post K, Sparrevohn CR, van der Meij M. A new era for science-industry research collaboration–A view towards the future. Frontiers in Marine Science. 2023;10: 1144181.

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