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A Brief Overview of Technologies in Automated Agriculture: Shaping the Farms of Tomorrow

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ABSTRACT

As global population continues to grow, there is an increasing need for innovative solutions to enhance agricultural productivity, efficiency, and sustainability. To meet increasing population demand, agricultural production must be doubled. The global population is projected to rise by almost two billion individuals within the next three decades. With global challenges such as population growth, climate change, and resource formation, automation in farming practices is one of the key driving forces behind this revolution. Robotics, coupled with artificial intelligence (AI) and

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advanced data analytics, are transformative solutions for precision farming and smart farming technologies. These technologies enable continuous and efficient farming operations and provide detailed monitoring at a plant-by-pant level, optimizing resource use and reducing the environmental footprint. Technological advancements have led to the development of various robotic systems, including agricultural grippers and autonomous machinery, which are integral to the automation of farming tasks, from sowing to harvesting. However, the adoption of such technologies is not without challenges. High initial investment costs, connectivity issues, and data security are some of the barriers that need to be addressed. The potential benefits of reduced operational costs, improved crop quality, and enhanced farm output make it a promising solution for the future of farming. In this article, we discuss the multifaceted role of robotics in modern agriculture by exploring both technological advancements and challenges to widespread adoption.

Keywords: Agricultural productivity; artificial intelligence (AI); automation in agriculture; robotics; sustainability; technological advancement.

1. INTRODUCTION

Robotics in farming is changing the way food is grown. It includes everything from machines that plant and harvest crops themselves to advanced methods that make farming more precise. These robots and techniques are improving farming by solving big problems and helping farms run more smoothly, produce more, and harm the environment less. Robots in farming have many different uses, all of which aim to make farming more efficient, productive, and eco-friendly [1,75]. Moreover, the integration of green nanotechnology into agriculture, utilizing biosensors and green-synthesized nanomaterials, further supports the eco-friendly aspect of robotic farming by reducing excessive pesticide use and enhancing crop productivity [2]. The integration of robotics into agriculture is driven by the need to address various challenges such as labor shortages, the environmental impact of traditional farming methods, and increasing food demand [1,3,147,148,149,150]. A key use is for robots that work independently in the field. These robots have tools such as sensors, cameras, and GPS to move around, spot plants, and perform tasks such as seeding, getting rid of weeds, and spraying very accurately. They help reduce the need for people to work in the fields, lower the money spent on materials, and increase the amount of crops grown, while being better for the environment. Robotics in agriculture encompasses a broad spectrum of applications, including, but not limited to, autonomous navigation, precision farming, and real-time data analytics, which collectively contribute to the optimization of crop management and productivity [4,5,81,82]. Interestingly, while the potential benefits of agricultural robotics are vast, the adoption of such technologies is not without limitations and requires significant capital investment. Moreover, the development of agricultural robots, or 'agribots,' is not only a technological endeavor but also a socio-economic one, as it necessitates acceptance and accessibility within the farming community, particularly in agriculture-based societies like India [6,7]. The role of robotics in agriculture is further complicated by the need for innovation in technology and adaptation of farming practices to meet the challenges of modern agriculture [8]. The role of robotics in agriculture is multifaceted, offering solutions to enhance productivity, sustainability, and profitability. The integration of advanced robotics and AI in farming operations is poised to revolutionize agricultural practices, making it a critical area of research and development for the future of food security and environmental stewardship [9,10].

2. PRECISION FARMING

Precision farming, also known as precision agriculture, employs detailed site-specific information to optimize agricultural practices. Robotics play a pivotal role in this domain by enhancing the precision and efficiency of various farming operations [4,11,12]. Precision Agriculture (PA) encompasses a range of technologies and methodologies aimed at increasing the precision and control of farming operations. This includes autonomous machinery for planting and harvesting, as well as advanced techniques for monitoring and managing crops [13,14,85]. Precision farming, enabled by robotic technologies, has emerged as a game-changer for agriculture. Robotic systems equipped with sensors, cameras, and other advanced technologies can be used to collect real-time data regarding weather patterns, crop health, and soil conditions. These data are then analyzed to make informed decisions, allowing farmers to optimize resource use, minimize waste, and enhance the overall crop yield. The integration of robotics into agriculture has been instrumental in automating tasks such as planting, harvesting, and pest control, thereby improving productivity and sustainability [1,15,83]. Precision agriculture (PA) not only enhances productivity but also minimizes environmental effects, making farming more sustainable in the long run [84]. Currently, drones equipped with various sensors and cameras are used to gather information regarding soil conditions, crop health, and other relevant parameters. They can cover the efficiency of large agricultural fields and provide farmers with valuable information for decision-making.

Many well-known and new farming businesses are putting money into creating new types of farming robot. For example, in 2021, a company called AGCO Corporation started testing a new system called the Precision Ag Line [PAL]. This system helps farmers who use different types of machines and services from AGCO obtain better support. Interestingly, while the benefits of robotics in precision farming are well documented, including increased yield, reduced environmental impact, and 24/7 operational capabilities, there are challenges such as high initial investment costs, the need for sophisticated algorithms, and AI to control these systems [1,16]. Moreover, the adoption of robotics in agriculture is not uniform across farming systems, with pasture-grazed agriculture facing unique challenges in technology adoption [16]. While PA offers significant advancements in efficiency and sustainability, it also presents challenges such as the need for technological adoption and the management of data privacy and security [17]. Interestingly, the integration of IoT and AI within PA not only optimizes resource use but also facilitates real-time decision-making and predictive analytics, which are crucial for modernizing traditional agricultural practices [18,19,86,87]. Robotics is a transformative force in precision farming that offers significant advantages in terms of efficiency and resource management. However, the adoption of such technologies is accompanied by economic and technical challenges that must be addressed. The future of precision farming is likely to be shaped by the continued evolution and integration of robotics, with a focus on sustainability and meeting the increasing global food demand [1,3,4,5,11,12,20].

3. AUTONOMOUS VEHICLE & MACHINERY

Autonomous vehicles and machinery are becoming increasingly central to the role of robotics in agriculture, as they are designed to perform a variety of tasks with minimal human intervention. The application of these technologies aims to enhance the efficiency and productivity of farming operations [21]. Precision agriculture, which involves precise management of farming practices, is a key area in which autonomous machinery makes significant contributions. These machines are equipped with advanced sensors and control systems that allow tasks such as seeding, weeding, and harvesting to be carried out with high precision [22,23,81].The incorporation of autonomous vehicles, such as unmanned aerial vehicles (UAV) and unnamed ground vehicles (UGV), in precision agriculture facilitates well-informed decisions regarding fertilizer, irrigation, and pest control. This approach optimizes resource utilization and enhances productivity. The vehicle is equipped with various sensors and imaging devices that can collect data related to soil health, crop conditions, and overall farm performance. However, transitioning to fully autonomous vehicles in agriculture is challenging. Currently, agricultural vehicles are mostly manned, and the shift to autonomous performance requires overcoming technical hurdles related to environmental sensing and task execution [22]. Moreover, the development of humanlike manipulation capabilities and harvesting robots remains a long-term challenge that must be addressed for robotics to penetrate the agricultural sector fully [24].

Fig. 1. Air spraying of pesticide with the help of drone

4. SEED MAPPING

Seed mapping is an application of robotics in agriculture that involves precise placement and tracking of seeds within a field. This process is integral to modern farming practices as it contributes to efficient land use and optimized growth conditions, leading to improved crop yields [3,25]. Seed mapping is a way to track where each seed is planted using GPS technology. Here, how does it work in simpler terms.

Imagine planting seeds in the field. As each seed is planted, a special GPS device on the planting machine takes note of the exact spot where the seed falls. This is done with the help of sensors that notice when the seed passes by, such as by breaking an invisible line. This information is saved by a computer that keeps track of the direction in which the machine is moving. Sometimes, when planting, the machine may tilt slightly because of uneven ground, which can mess the GPS readings. To fix this, a tool called inclinometer is used. It measures the extent to which the machine tilts and helps correct the GPS data. [26]. All of these data are collected very quickly, and later, computers use these data to determine exactly where each seed ends up. This is helpful because later, when it is time to take care of the plants, such as watering or adding nutrients, you can be very precise and go straight to where the plants are growing. This makes farming more efficient and can help the plants grow better [26].

5. WEED MAPPING

Weed mapping is similar to creating a detailed map of where weeds grow in a field. It uses cameras to spot weeds and determine the number and type of weeds. Autonomous robotic systems are being increasingly developed to address this task, which is essential for precision agriculture and sustainable farming practices [27]. The current practice of pesticide application in agricultural fields often involves spraying the entire area without detailed checks or targeted application [28,29]. This approach can lead to inefficiencies such as overuse of pesticides, increased costs, and potential environmental harm [28, 30]. Advancements in technology, such as GPS-guided spraying machines and autonomous pesticide spraying robots, have been designed to address these issues by enabling precise and efficient pesticide applications [28,31]. These technologies can reduce the amount of pesticides used and mitigate the risk of environmental damage by ensuring that pesticides are applied only when needed [30, 31]. However, the adoption of such technologies is not yet widespread, and many farmers continue to rely on traditional, less-precise methods [32,29]. The use of weed maps has some significant benefits [26,139,140].

- It helps to plan how to control weeds better and to take care of the environment.
- This provides a clear picture of where weeds reside in natural areas.
- It tracks how weeds spread and if efforts to control them are working.
- This pinpoints exactly where the weeds are located.

These systems utilize core technologies such as machine vision and GPS to detect and map weeds, aiming to reduce reliance on herbicides and improve environmental outcomes [25, 27]. However, the challenge of accurately detecting and identifying weeds under various field conditions remains a significant hurdle. Despite these advancements, complete robotic weed-control systems that can effectively map weeds in diverse agricultural settings are still in the developmental stage, necessitating further research [27]. Moreover, the integration of deep learning models in autonomous robots shows promise for real-time weed detection, which is a crucial step towards efficient weed mapping [33,34].

6. WEED AND PEST CONTROL

Weed and Pest Management have long been a major challenge in agriculture. Traditional pest control methods typically involve extensive use of herbicides and pesticides, which present significant environmental hazards. Robotic systems offer a targeted and sustainable approach. Robotics weeders utilize artificial intelligence (AI) and computer vision to distinguish between crops and weeds, selectively removing unwanted plants without harming the main crop. Similarly, autonomous robots equipped with precision spraying systems can be used to target specific areas and apply pesticides with unprecedented accuracy. Robots equipped with sensors and artificial intelligence can identify and target weeds, thereby reducing the need for chemical herbicides and minimizing environmental impact [35, 36,88]. Moreover, the use of robotics in pest control can lead to more effective monitoring and management, potentially reducing reliance on pesticides and contributing to sustainable farming practices [37]. There are different ways to manage weeds without using chemicals. For example, one can push the right around the weed's roots to dry out and die.

There are three main areas where weeds can be treated in the field:

i) **Inter-row area:** The inter-row area refers to the space between planted rows of crops, where mechanical weed control methods such as harrowing, inter-row cultivation, and mowing have traditionally been used [38, 39].
ii) **Intra-row area:** The intra-row area is the space within the crop row itself where weeds are more challenging to manage because of the risk of damaging the crop. Novel mechanical and automated systems have been developed to address weed control in this area, such as an automatic tillage system with real-time kinematic GPS navigation [40], and a mechanical intra-row weeding prototype using rollers and ultrasonic sensors [41].
iii) **Close-to-crop area:** The close-to-crop area is immediately adjacent to the crop plants, where precision is paramount for avoiding crop damage. Intelligent weeders and advanced technologies such as sensor-based systems and robotics are being developed to improve weed control in this zone without harming crops [42,43].

Interestingly, although mechanical weed control is effective, it is not without challenges. For instance, relying solely on inter-row data for weed detection could underestimate weed pressure because weeds are often more abundant within rows [44]. Furthermore, the effectiveness of mechanical weed control can be affected by a range of factors, such as the soil resistance of crops and weeds during cultivation, and competitive interactions between crops and weeds. [39]. Although robotics presents a promising avenue for weed and pest management, there are considerations regarding the cost of implementation and the ability of the technology to integrate with existing agricultural systems [1,5]. Additionally, the application of robotics for these purposes is still in the developmental stage in some agricultural contexts, indicating the need for further research and adaptation to diverse farming environments [35].

7. CROP SCOUTING

Crop scouting is an essential agricultural practice aimed at assessing and managing pest pressure, disease outbreaks, and overall health within crop fields. It involves regular and systematic field inspections to identify and evaluate the factors that could affect crop yield and quality [45,89]. Robotics plays an increasingly significant role in this domain, offering precision and efficiency that manual scouting cannot match. Agricultural robots equipped with advanced sensors and imaging technologies can traverse fields and collect data that are then analyzed to inform decisions regarding crop management [25, 46, and 47]. SentiV is a robotic scout designed to identify variations in crop fields and pinpoint potential risks to the plants. The robot is equipped with two cameras that scan over and under the foliage [48]. Reconfigurable ground vehicles (RGVs) have been developed to navigate through crops, providing real-time data on pest infestation, soil moisture, and disease severity, which facilitates timely and informed decision-making [48]. Additionally, precision agriculture technologies integrate various data sources, including remotely sensed data, to proactively manage crops and prevent damage, thereby optimizing resource use and environmental protection [49]. Interestingly, while the integration of robotics in crop scouting enhances data acquisition and analysis, it also presents challenges, such as the need for sophisticated algorithms for object identification and task planning. Moreover, the development of multi-robot systems and human-robot collaboration is seen as a gateway to more advanced digital farming practices, including crop scouting [46,47]. However, the expectation of fully automated farming systems remains unrealistic in the near future, indicating that human oversight and intervention are necessary [46,47].

Fig. 2. Scouting Robot
Source: -https://meropy.com/en/robot.html

8. DATA DRIVEN DECISION MAKING

Data-driven decision making (DDDM) in agriculture, particularly when integrated with robotics, represents a significant advancement in the sector. Robotics equipped with sensors and

AI technologies can collect and analyze vast amounts of data, leading to more informed and precise farming decisions [50, 51,83]. These decisions range from optimizing resource allocation to identifying the best time for planting and harvesting. The integration of robotics into farming operations facilitates comprehensive monitoring and data analysis**.** It can produce copious amounts of data pertaining to crop health, soil conditions, and weather patterns. Unmanned aerial vehicles (UAVs) and land-based robotic systems equipped with imaging and sensory equipment can capture high-definition images and gather valuable data pertaining to crop health, growth patterns, and potential issues [18,52].

Analyzing these data using artificial intelligence enables farmers to make data-driven decisions, identify early signs of disease or nutrient deficiency, and implement timely interventions. Farmers can leverage these data to gain insight into crop performance, resource utilization, and environmental conditions. By employing data analytics and artificial intelligence, farmers can make informed decisions about irrigation, fertilization, and crop rotation, leading to optimized agricultural practices. Moreover, the application of DDDM in agriculture is not without ethical considerations, particularly concerning data privacy and the potential displacement of human labour [53,90,91].

9. SMART IRRIGATION SYSTEM

Water scarcity is a significant concern in agriculture, and robotic technology plays a crucial role in addressing these challenges.

Smart irrigation systems are a critical component of robotics in agriculture, offering a technologically advanced solution to manage water resources efficiently. These systems utilize sensors and automation to optimize water usage, ensuring crops receive the precise amount of water needed for growth [54,55,56]. The integration of robotics in these systems allows for the precise control and monitoring of irrigation, contributing to the broader concept of precision agriculture [12]. This helps in not only conserving water but also to ensure that the crop receives the optimal amount of irrigation, thereby improving crop yield and resource efficiency. Interestingly, while smart irrigation systems are promising for enhancing water management, their implementation is challenging. Initial capital investment and the need for technical expertise can be barriers, particularly in developing countries [57]. Moreover, the complexity of integrating these systems with existing agricultural practices requires careful consideration of local environmental conditions and infrastructure [15].

10. MICRO SPRAYING

Microspraying in agriculture refers to the precise application of agrochemicals or nutrients to crops, targeting specific areas or even individual plants to minimize waste and environmental impacts. Robotics plays a significant role in this domain by enhancing the precision and efficiency of the spraying operations. Agricultural robots equipped with advanced sensors and control systems can autonomously navigate fields, identify the need for spraying at the micro-level, and deliver the necessary substances with high accuracy [12, 25]. Microspraying is a precise way to deal with weeds, using a very small spray that targets only the weeds without hurting the crops or soil. It is similar to having a tiny spray gun that turns on and off to hit just the right spots. This method is smart because it uses cameras to find weeds and then sprays a little amount of weed killer right on the leaves. The cool part is that using a gel instead of water can make the spray even more accurate, so it does not splash everywhere. This helps to protect crops while eliminating weeds. Interestingly, while the use of spraying drones is highlighted for their speed and reduced water usage, they also face challenges such as limited battery efficiency [58,92]. Moreover, the integration of robotics in microspraying aligns with the broader objectives of precision agriculture, which aim to optimize resource use and improve crop management through technology [4, 22].

11. LABOUR SHORTAGES AND INCREASED EFFICIENCY

In recent times, fewer people have been interested in farming, and many farmers are becoming older. This has led to a reduction in the number of farm workers. Farmers are struggling to grow enough food to meet increasing demand because there are not enough workers. In addition, because there are fewer workers, wages for farm labour are increasing, and in countries like the United States and the United Kingdom, farming relies heavily on workers. This is also true in other developed countries. The World Bank states that the number of people working in agriculture has decreased by 15% in the last ten years worldwide. The shortage of workers is a big issue everywhere, and it is made worse by the fact that many farmers are older, which means there are not enough people to do manual work on farms [124,125,126, 127,128,129]. In the Saxon Freestate, a survey from 1922 highlighted a dire shortage of nearly 19,000 workers, particularly young, single women, which farmers linked to the potential ruin of family farms [124]. Similarly, in Korea, the agricultural industry is predominantly managed by those over 65, and the aging of farm households is expected to intensify, necessitating an environment that supports continued engagement of aged farmers in agriculture [125].

In some regions, labourers are available, but they are not skilled [130,131]. The integration of robotics in agriculture has been identified as a key factor in addressing labour shortages and increasing efficiency in the sector. Advanced robotics, controlled by sophisticated algorithms and AI, offers precision farming capabilities that enhance yield and quality, while minimizing waste and environmental impact [1]. These technologies enable continuous farming operations, overcoming the limitations of human labour such as working hours and physical exhaustion [1]. Moreover, the adoption of agricultural robotics can lead to reduced operational costs and enhanced farm outputs, which is crucial given the rising global food demand and need for sustainable practices [1]. Interestingly, while robotics in agriculture presents a promising solution to labor shortages, it also requires a strategic approach to workforce development. The integration of robotics in manufacturing, for instance, has shown that although automation can eliminate routine tasks, it also requires upskilling of the workforce to operate and maintain these systems [59]. This suggests that the agricultural sector may face similar challenges and opportunities, highlighting the need for investment in education and training to prepare the workforce for a collaborative future with robots [60].

12. GREEN HOUSE AND INDOOR FARMING

We have observed the role of robotics in outdoor farming. In addition to outdoor farming, robotics play a significant role in greenhouse and indoor farming. Automated systems help in managing environmental variables, such as temperature and light, and creating optimal conditions for plant growth. This level of control enhances year-round production, reduces resource consumption, and provides a solution for farming in areas with challenging climates. Greenhouse and indoor farming represent a significant shift in agricultural practices, moving towards controlled environment agriculture (CEA), where conditions can be optimized for plant growth. Robotics plays a crucial role in these settings by automating tasks, enhancing resource efficiency, and improving productivity [61, 62,93,94]. In greenhouses, robots can regulate the climate, manage irrigation, and monitor plant health, thereby reducing the need for manual labor and increasing the precision of environmental control [46, 47]. Interestingly, while the adoption of robotics in agriculture promises numerous benefits, it also presents challenges such as high initial costs and the need for technical expertise [15]. Moreover, the integration of advanced technologies such as IoT and AI in indoor farming facilitates the development of smart agricultural systems that can learn and adapt to optimize growth conditions for various crops [63,95,96,97]. In conclusion, the role of robotics in greenhouses and indoor farming is pivotal for the advancement of modern agriculture. Robotics contributes to the sustainability and efficiency of food production systems by enabling precise control over farming conditions and reducing the environmental footprint. As technology continues to evolve, the potential for robotics to revolutionize agriculture and meet increasing global food demand has become more apparent [1,5,98].

Fig. 3. Indoor farming robots
Source: - Sompong Rattanakunchon / Getty Images

13. LIVESTOCK MANAGEMENT

Livestock management in the context of agricultural robotics is an area where significant advancements have been made. Robotics and AI have been instrumental in transforming livestock management by enhancing productivity, improving animal welfare, and contributing to sustainability [57]. The deployment of robots in the livestock sector, as detailed by Billingsley [65], includes applications for feeding, milking, and monitoring animal health, which are critical for efficient farm operations. Robotic milking machines, for example, allow for more frequent and efficient milking, improving overall dairy farm productivity. According to the World Robotics Report 2022, India is positioned as the 10th country worldwide in terms of annual industrial installations.

Furthermore, wearable sensors and smart collars equipped with GPS technology enable farmers to track the health and location of individual animals, ensuring timely veterinary intervention and minimizing the risk of disease outbreaks. Interestingly, while the integration of robotics in livestock management promises numerous benefits, there are also challenges such as high initial costs and the need for technical expertise [65]. Moreover, farmers' perspectives on the adoption of these technologies vary, with some expressing skepticism about the reliability and safety of using agricultural robots on their land [66]. In summary, the role of robotics in livestock management is multifaceted, offering improvements in efficiency and productivity while also presenting challenges that need to be addressed. The potential of robotics to revolutionize livestock management is clear, with the potential to enhance animal welfare and meet increasing global food demands in a sustainable manner [67,68]. However, the successful integration of these technologies into agriculture requires careful consideration of the economic and social implications as well as the perspectives of the farming community.

Fig. 4. Cow inoculation process using a Fanuc industrial robot
Source: - (therobotreport.com)

14. HARVESTING AUTOMATION

Harvesting automation represents a critical application of robotics in agriculture, with the aim of enhancing efficiency and addressing labor shortages. The integration of robotics in harvesting processes is driven by the need for precision, speed, and consistency, which are difficult to achieve with manual labor alone. Robotic systems are designed to perform tasks such as identifying ripe produce, precision picking, and in-field grading, which contribute to increased productivity and reduced waste [1,64]. Interestingly, although the potential benefits of harvesting automation are significant, the adoption of such technologies is challenging. The diversity in crop types and complexity of harvesting tasks require advanced sensing, localization, and manipulation capabilities of robots. Moreover, initial capital investment and the need for skilled personnel to operate and maintain these systems are notable barriers to their widespread adoption [46,47,69]. Harvesting automation through agricultural robotics offers a promising avenue for improving the efficiency and sustainability of farming operations. This technology has the potential to revolutionize the agricultural sector by providing solutions to labor shortages, enhancing yield quality, and reducing the environmental impact of farming practices. An automated harvesting machine, guided by advanced computer vision and robotic arms, can selectively pick ripe fruits or vegetables with unparallel speed and accuracy. This not only addressed labor shortages but also ensured a more efficient and cost-effective harvesting process. However, the successful implementation of these systems hinges on overcoming the technical and economic challenges. Future advances in robotics may facilitate the integration of autonomous harvesting systems into the agricultural industry [70,103].

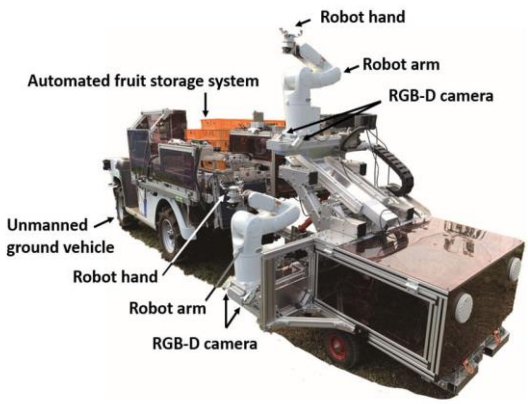

Fig. 5. Fruit harvesting robot
Source: - (NARO or National Agriculture and Food Research Organization)

Table 1. Employing robotic technology for agricultural processes

S. No	Robot type	Description	Tools Image
1	solar-electric Digital Farmhand	Mechanical weeding tools can target and remove weeds one by one. The concept of a solar-electric Digital Farmhand aligns with the broader trend of integrating photovoltaic (PV) technology into agricultural machinery to enhance sustainability and reduce reliance on fossil fuels [132]	 *Source: Agerris (2020) https://www.linkedin.com/feed/update/urn:li:activity:6673707377046495233/*
2	A small robot from France, named OZ.	The NAIO Technologies Oz robot is an autonomous weeding robot that has been successfully tested using a LiAR-based navigation approach [133]. This tool can remove weeds from rows of crops and among trees in orchards without harming the plants.[133]	 *Source: Naio Technologies(2016) https://www.futurefarming.com/tech-in-focus/field-robots/lets-start-with-robots-for-smallholder-farms/*
3	Smartcore Robot	Smartcore is a tool that accurately gathers consistent soil samples from fields and delivers them straight to the farmers[134]	 *Source: Purdue Research Foundation image/Oren Darling https://www.purdue.edu/newsroom/releases/2019/Q3/autonomous-robots-enter-fields-to-collect-precise-soil-samples,-help-farmers-improve-yields,-reduce-environmental-impact,-save-money.html*
4	MF-Scamp robots	This robot is designed for scouting fields, removing weeds, and harvesting crops. It uses a color sensor to distinguish weeds from crops [99].	 *Source: Prof. Simon Blackmore, Harper Adams University, England, 2018*

S. No	Robot type	Description	Tools Image
5	Robotic Precision Planter	Developed by ICAR-IARI in New Delhi. It uses a system based on Cartesian coordinates to ensure each seed is placed at the right depth and distance apart, forming the correct pattern for the crop [100].	 *Source: https://www.researchgate.net/profile/HKushwaha/publication/339428195/figure/fig4/AS:861316843585536@1582365346519/Robotic-Precision-Planter-IARI-New-Delhi.png*
6	Rice Transplanter Robot	Rice seedlings are moved from small nursery boxes to the larger paddy field. During this process, a white box filled with insecticide is used to lightly cover the seedlings with the chemical to protect them from pests as they grow [101].	 *Source https://www.researchgate.net/profile/HiroshiJinguji/publication/281704745/figure/fig2/AS:475235548962818@1490316392779/Nursery-boxes-for-rice-cultivation-top-and-rice-seedlings-separated-for-the-micro-paddy.png*
7	Swagbot	SwagBot is a robot that can track cattle and maybe sheep too. It can move over rough ground smoothly. It helps to lead the cows to grazing areas and keep them away from danger [102].	 *Source: Courtesy of Australian Centre for Field Robotics, The University of Sydney*
8	Demeter	The given Figure shows a harvester, which is a New Holland 2550 Speedrower. It is used for harvesting purpose. It has been updated with wheel encoders and servos. These additions help control several parts of the	

S. No	Robot type	Description	Tools Image
		machine, like the speed, direction, and the cutting blade [103].	*Source: https://www.researchgate.net/profile/Mark-Ollis/publication/3731308/figure/fig1/AS:333402420072449@1456500739101/The-Demeter-automated-harvester.png*
9	solar-powered Vitirover robot	The Vitirover is a robot that cuts grass without needing harmful chemicals. It can trim the grass very close to the base of vine plants. The robot gets its power from solar panels on its top. It uses GPS to move around safely, avoiding any gaps or holes. You can also control it with a smartphone app [81,104,105].	 Source:https://www.researchgate.net/profile/Paolo-Visconti-2/publication/342438120/figure/fig6/AS:907676552818688@1593418362143/Image-of-solar-powered-Vitirover-robot-in-action-on-the-ground-a-Falcon-8-drone.ppm
10	Field Work Robot	It is used to gather information about crops, spot diseases, and steer clear of obstacles [106].	 *Source: Amazone GmbH & Co. KG https://commons.wikimedia.org/wiki/File:Amazone_BoniRob_Feldroboter-Entwicklungsprojekt.jpg*
11	**Bee Drone**	Tiny robots have been designed with horse hair and a special sticky substance that lets them pick up pollen from one flower and move it to another, these robots are being used to help with the pollination of farm crops, which is usually done by bees [107].	 Source:https://www.purdue.edu/fnr/extension/wp-content/uploads/2017/07/robot-butterfly.png

S. No	Robot type	Description	Tools Image
12	Robotic gripper	A robotic gripper is a basic mechanical hand created to learn how to grab and carry various items. It's built to handle and move objects with different shapes and sizes [108].	 *Source: https://www.wisematic.com/wp-content/uploads/2020/04/mGrip-Iceberg-Lettuce-scaled.jpg*
13	Monkeybot	A Climbing and Pruning Robot for Standing Trees in Fast-Growing Forests [109].	 Source:https://www.researchgate.net/publication/364281240/figure/fig7/AS:11431281088797158@1665321517675/Forest-test-operations-a-Late-spring-pruning-b-winter-pruning.png
14	Vegebot	A vegetable-picking robot that can pick vegetables. It uses a special kind of artificial intelligence called machine learning to recognize and collect crops that are usually tough to gather by hand [85,110,111].	 *Source: university of Cambridge https://www.cam.ac.uk/research/news/robot-uses-machine-learning-to-harvest-lettuce*
15	FFRobot	FFRobotics introduces the FFRobot, a special and patented machine designed to harvest fruit. It's a sturdy and dependable system that mimics the gentle touch of human hands, ensuring an efficient, affordable, and gentle fruit picking process. [135,136,137]	 *Source: https://www.ffrobotics.com/*

S. No	Robot type	Description	Tools Image
16	R2Weed2	Nexus Robotics has developed an autonomous robot named R2Weed2 that uses artificial intelligence to tell weeds apart from crops. This allows it to remove the weeds while leaving the crops unharmed. Additionally, as it operates, R2Weed2 collects valuable data that assists farmers in analyzing soil conditions and monitoring the environment [112].	 *Source: https://nexusrobotics.ca/wp-content/uploads/2024/02/53495961299_d2170b5b11_c-799x499.jpg*
17	Harvest CROO robot	Harvest CROO is a company that's created a smart robot to pick strawberries. This robot has many parts that work together to gently pick the fruit and put it in a package. It uses special cameras to tell which strawberries are ready to pick. This robot is really quick, taking only about eight seconds to pick each strawberry plant, which is faster than people doing the same job [112].	 *Source: Harvest CROO https://www.harvestcroorobotics.com/*
18	Carbon Robotics' LaserWeeder	LaserWeeder is a tool that uses artificial intelligence and special cameras to tell the difference between crops and weeds. It then uses lasers to get rid of the weeds without hurting the crops. The company behind it claims that this technology not only makes the crops better but also cuts down on farming costs [113].	 *Source: Carbon Robotics https://carbonrobotics.com/*
19	electric mower	Scythe Robotics has developed an electric mower that works on its own to maintain properties in a way that's both effective and eco-friendly. Their M.52 mower model comes with twelve sensors that give it a full view of its surroundings. It also has smart artificial intelligence that helps it move around any barriers it might come across [114].	 *Source: Scythe Robotics https://www.scytherobotics.com/*

S. No	Robot type	Description	Tools Image
20	Naio Technologies-Ted	Ted is an electric machine that looks like an upside-down 'U' and moves across and around vine rows. It uses advanced satellite navigation to keep on track, and drones help it map the land it covers. It has special blades and tools at the bottom that remove weeds from the vines, which helps reduce the use of weed-killing chemicals. [138]	 *Source: Naio Technologies https://www.naio-technologies.com/en/ted/*
21	American Robotics-UAS & UAVs	American Robotics has created Scout, a drone that stays in a protective box where it charges and analyzes data. It flies autonomously to check fields, using AI to navigate. Scout collects important information about the health of crops, which helps farmers manage their fields better [112].	 *Source: https://www.american-robotics.com/*
22	Wheat Precision Seeding Robot	Seed-sowing robots help farmers by planting seeds precisely where they need to go. This saves farmers time and money [115].	 *Source: https://www.researchgate.net/publication/284786330/figure/fig1/AS:1088549470375938@1636541826122/Wheat-precision-seeding-robot.jpg*
23	Tractor-mounted boom sprayer	Consist of a smart system that uses cameras to recognize crop rows and automatically turn on the pesticide sprayers. It works with smartphones and can be easily added to different kinds of sprayers on tractors. The system was tested on an onion farm and successfully controlled the sprayers by identifying the crop rows [116,117,118].	 *Source: https://www.researchgate.net/profile/Paulo-Drews-Jr/publication/339657662/figure/fig1/AS:982033379647492@1611146*

S. No	Robot type	Description	Tools Image
			411857/Tractor-mounted-boom-sprayer-10.jpg
24	Picking robot	Octinion, a company that works on agricultural research, has created a robot that can pick strawberries from raised platforms. This robot works all by itself: it can find strawberries that are ready to be picked, gently harvest them, and place them into a small box. It moves around the greenhouse on its own. The latest version of this robot can pick a strawberry in just 4 seconds [26].	 *Source: https://www.sciencedirect.com/science/article/pii/S2405896318311704?via%3Dihub*
25	Feed Pusher Robot	Used for feeding the cattle [33]	 *Source: https://www.mdpi.com/2076-3417/11/22/10665*
26	Tortuga Harvesting Robot	Tortuga AgTech has developed robots that assist in farming by automating the process of spotting and harvesting ripe fruits. These robots are designed to tackle issues such as the lack of available workers and increasing expenses. They also minimize the potential harm to fruits that might occur with manual picking. The company's robots can accurately pick fruits with a 98% success rate and only need one person to oversee their operation [84,119].	 *Source: Tortuga https://www.tortugaagtech.com/*
27	Digital FarmHand	The Digital FarmHand is a robot created for small farms by the University of Sydney. It does jobs like checking crops and making maps of fields. It can find and get rid of weeds all by itself, so farmers won't need to use as many weed killers. This could save money and be better for the planet.[132,139,140]	 *Source: University of Sydney*

S. No	Robot type	Description	Tools Image
			https://www.sydney.edu.au/engineering/our-research/robotics-and-intelligent-systems/australian-centre-for-robotics.html
28	AGRIM-X	AGRIM-X is a smart drone made by Suind for farming. This 10L Smart Agricultural Sprayer is a robot that can work on any farm, big or small. It's the beginning of making the best crop-protection tools out there. It's got smart eyes and brains (vision and AI) to work all by itself in any kind of field. It knows how to keep the right distance from plants, move around things in its way, and start and stop safely. It's super easy to use and makes spraying crops way more effective [31].	 Source: Suind https://suind.com/agrimx
29	Vision-RTK 2	Vision RTK Fusion is a cool tech made by Fixposition AG from Switzerland. It mixes up GPS with seeing stuff to get super accurate location info. It works great outside, under trees, between tall buildings, and even inside greenhouses and barns. It's really precise, which is perfect for jobs that need to know exactly where things are [120].	 Source:https://www.researchgate.net/profile/Lorenzo-Scalera/publication/362501601/figure/fig1/AS:11431281084675777@1663324424076/a-Agile-X-mobile-robot-in-the-corridor-of-test-case-1-b-point-cloud-of-the.jpg
30	TRAXX Concept H2 Prototype (Hydrogen-Fueled Vineyard Tractor)	The TRAXX Concept H2 is an innovative straddle carrier that operates using a combination of a fuel cell and batteries, providing a power output of 35kW. It's designed with two hydrogen tanks capable of holding over 9 kilograms of hydrogen, enabling it to run continuously for up to 12 hours. What makes this machine stand out is its hydrogen fuel source, which emits no pollution, making it an eco-	 *Source: Mick Roberts https://exxact-robotics.com/*

S. No	Robot type	Description	Tools Image
		friendly alternative to traditional gas and diesel. This feature is particularly appealing in the agricultural industry's shift towards sustainable practices. The use of hydrogen also contributes to the machine's lighter weight and quieter operation, while still maintaining efficient performance and quick refueling times.[141,142,143]	
31	Bluewhite Pathfinder	Bluewhite's Pathfinder is a cutting-edge system that upgrades regular tractors used in orchards and vineyards into a smart, self-operating fleet. These autonomous tractors can perform various agricultural tasks like spraying, spreading herbicides, discing, mowing, and harvesting with great accuracy and efficiency. The Pathfinder achieves this by integrating a variety of sensors, LIDAR, cameras, and GNSS technology, which allows it to navigate safely through different crops and terrains. This system is independent of GPS/RTK or cellular networks, ensuring reliable operation even in areas where such connections are unavailable. [144,145,146]	 *Source: https://www.bluewhite.co/*
32	Robot Apple Harvester 3	Researchers at Monash University have created a robot that can independently harvest apples. During tests at Fankhauser Apples in Victoria, the robot successfully picked apples with an 85% efficiency rate. It took about nine seconds for each apple to be picked and placed, even though the robot was only working at half its potential speed [100].	 Source: Monash University https://www.monash.edu/news/articles/advanced-core-processing-new-robot-technology-appealing-for-apple-growers

15. AGRICULTURE ROBOTS MARKET SCENARIO

It is expected that the market for farming robots will be worth approximately USD 14.97 billion in 2024. By 2029, it is predicted to grow to USD 27.71 billion, with an annual growth rate of 13.10% from 2024 to 2029 [121]. The International Federation of Robotics reports that China, South Korea, Japan, the USA, and Germany are the main countries in the market. Together, these constitute 74% of the total amount of products available. The market for farm tools in India is expected to expand a lot. The IMARC Group report predicts that, from 2024 to 2032, the market will grow at a rate of 9.1% each year, and by 2032, it could be worth INR 2,527.4 billion. This increase is likely because there are not enough farm workers, it is easier to obtain money to buy farm equipment, the government is offering help, farms are producing more, and there is a rise in contract farming. With new technologies and the increased use of machines, this is a promising period for farming in India [45].

16. FUTURE OF AGRICULTURAL ROBOTS

The future of agricultural robots is poised to be transformative, with robotics playing an increasingly important role in agriculture. Agricultural robots are expected to enhance farming productivity through advanced technologies such as sensing, artificial intelligence (AI), and autonomous navigation [3,71]. These technologies will enable precision agriculture and optimize farm management practices to achieve high efficiency and sustainability [11]. Agricultural robots, often called “agribots,” is shaping up to be quite innovative and transformative for farming. Agribots are set to play various roles in agriculture, from surveillance drones to precision weed control, crop harvesting, and planting. These robots will use artificial intelligence to perform tasks more efficiently, helping to address challenges such as labor shortages and environmental concerns. For example, robots that can identify and spray weeds with pinpoint accuracy are already being developed, thereby reducing the need for herbicides. There are also robots designed for picking fruits and vegetables that can help with labor-intensive farming [122].

High-throughput plant phenotyping (HTPP) is a modern farming technology that combines genetics, sensors, and robots to create improved crops. It helps scientists make new types of crops that are more nutritious and can survive harsh conditions, such as dry weather and pests. HTPP uses many sensors to check how the plants look and grow, such as how tall they are, how many leaves they have, and what color they are. These details are called phenotypic traits, which are visible features of a plant’s genetic makeup. By examining these traits, scientists can determine which plants possess the best genes for certain qualities [29].

In the near future, we expect these robots to become more common on farms, working alongside farmers to make agriculture more sustainable and productive [97,123]. They’ll be equipped with advanced sensors and data analysis tools to make smart decisions on the spot, leading to less waste and better crop management. However, the integration of AI into agricultural robots remains a challenge, limiting their application in low-volume production [71]. There are also ethical and policy questions to consider, as the widespread adoption of robots in agriculture has social, cultural, and security implications [72]. Moreover, the perspective of farmers regarding the deployment of robots and automation is crucial because their acceptance is necessary for the successful implementation of these technologies [66]. Overall, agribots are poised to revolutionize the way we farm, making it more efficient, less resource-intensive, and more in tune with the environment [80].

17. CHALLENGES AND CONSIDERATION

Agricultural robots are being increasingly recognized for their potential to address various challenges in the farming sector. The role of robotics in agriculture extends from land preparation to harvesting, offering solutions to labor shortages, enhancing productivity, and reducing the environmental impact of farming practices [3]. However, adoption of these technologies is challenging. One significant challenge is the complexity of the agricultural environment, which is both dynamic and unstructured. This complexity can hinder the performance of fully autonomous robots, leading to the exploration of teleoperation as an alternative to improve navigation and task execution, such as spraying grape clusters in vineyards [73]. Additionally, the socioeconomic effects of automation, including labor displacement and the need for substantial technological investment, must be considered

[74]. The integration of robotics into modern farming brings about numerous benefits, but there are challenges that need to be addressed. Initial investment cost, need for specialized training, and skilled operators about the challenges faced by farmers adopting robotics technologies [77,78].

Robots used in agriculture (RA) require routine maintenance to work well. People with a basic education need to build, fix, and improve these robots. Because each robot has a specific job, research is important to make them do more. Therefore, it is important to teach farmers how to use and manage robots. Agricultural robots (AR) cost more than old-school farming, so non-profits, banks, and the government help by investing in or giving loans with low interest. Farmers should receive special training on AR from experts for proper use. The technology discussed should be available everywhere, even in isolated areas, to assist farmers and keep them informed of new farming methods. Farmers should connect with local experts and businesses to stay informed about farming advancements [76].

Moreover, there are concerns about data security, ethical considerations related to automation, and potential impacts on rural employment. The integration of cloud robotics in agriculture also faces challenges such as cost, connectivity, and data security concerns [65]. Moreover, the adoption of robotics in pasture-grazed agriculture is emerging, with developers facing challenges related to the complex nature of biological systems and the relative cost of technology versus farm labor costs [16]. The development of digital farming technologies, such as autonomous weed control and harvesting, is also confronted with challenges in object identification, task planning algorithms, and sensor optimization [46,47,79]. Farmers' perspectives on automation and concerns about safety and reliability further influence the adoption of agricultural robots [66]. Additionally, there is a continuous need for research to enhance the capabilities of robotic systems and address specific challenges in diverse agricultural environments [78].

18. CONCLUSION

The integration of robotics into modern farming represents a transformation shift that holds immense promise for agriculture. As the world grapples with the challenges of feeding a growing population and addressing the impact of climate change, the integration of robotic technologies in agriculture provides a promising solution. Robotics plays a pivotal role in transforming the way we produce food from precision agriculture and automated harvesting to weed control and pest management. With ongoing advancements and innovations, the future of farming is becoming increasingly automated, smart, and resilient, which enables farmers to not only enhance productivity but also foster a more sustainable and resilient food system worldwide.

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.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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