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TOPICAL REVIEW

Advancements in Precision Spraying of Agricultural Robots: A Comprehensive Review

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ABSTRACT Through mechanization, automation, and intensification, there has been a substantial increase in agricultural production over time. The efficiency, reliability, and precision of agricultural equipment have improved significantly with automation, leading to a reduced dependency on human intervention. The surge in the adoption of agricultural robotics research and technologies is a response to the growing recognition that robots offer an effective solution to address the shortage of skilled workers in crop production. This paper aims to present a systematic overview of recent advancements in precision delivery technology within agricultural robotics, with a primary focus on the following aspects: 1) precision agriculture market; 2) design and development of spray robot technologies, encompassing both terrestrial and aerial platforms; 3) spray technologies and their application mechanisms; 4) various spraying techniques tailored to specific pests and vegetation; and 5) evolution of sensor technologies for precision spraying. Additionally, this article explores the current state of the art in robotic technologies employed in precision agriculture.

INDEX TERMS Precision agriculture, agricultural robotics, precision spraying, precision delivery, sensor technologies, spray robots, terrestrial and aerial platforms.

I. INTRODUCTION

The automation has made agricultural machinery more dependable, accurate, and efficient, requiring less human intervention [1]. A chronic manpower shortage still severely affects agriculture, especially the horticultural sector. A lack of workers makes farming even more difficult. Traditional farming, which involves farmers manually cultivating and managing crops, can be much more productive when intelligent machines are used [2]. Trends like growing farms, fewer farmers, and the growing environmental effects of food production all exacerbate the challenges posed by a lack of workers. In addition, pushing beyond the incredibly productive levels of conventional crop farming calls for developing a new agricultural system that uses cutting-edge automated procedures to do away with human involvement [3].

In the context of precision agriculture, robot employment seems to be a viable choice because it allows repetitive labor to be completed throughout the working day without compromising precision [4], [5]. A variety of robots are available for purchase these days, and robotics research is seeing an increase in the use of these robots [6]. Agricultural robotics aims to do more than just use robotics in farming. Today, the majority of agricultural vehicles are operated by hand to carry out various activities such as plant disease detection [7]. weed identification, pesticide distribution, terrain levelling, land irrigation, and other duties. Since these autonomous robots could independently gather information about their surroundings and use that information to complete their tasks, they would enable continuous field management as well as greater productivity and efficiency [8]. In order for robots to function well in agricultural environments and

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perform agricultural tasks, research needs to concentrate on the following areas: designing basic manipulators to perform the required agricultural activity; developing path planning, navigation, and guidance algorithms tailored to scenarios other than open fields; integrating with workers and operators in this intricate and dynamic scenario; and integrating multiple complementary sensors to achieve acceptable localisation and monitoring abilities. This is the main objective of using a range of technologies meant to reduce agricultural costs and increase crop quality and output. The main long-term goal of ensuring food security in the face of climate change is to transform the current agricultural paradigm, which emphasizes reducing the use of natural resources while boosting crop output [9], [10]. For instance, [10] showed that precise treatment application, which consists of adding water and plant nutrients only when and where needed by the crop, when combined with precision seeding and planting, increases average plant size and uniformity of plant maturity and decreases the ratio of water and phytosanitary products to crop production and, consequently, the environmental impact. Additionally, according to recent studies, using robots or autonomous tractors to carry out various agricultural jobs reduces pollution and fuel consumption [11], [12].

Agricultural autonomous vehicle research began in the early 1960s and focused on developing automatic steering systems [13]. The vast majority of mechanical field crop farming operations in the 1990s employed large, robust, high-capacity gear that required a lot of energy and had significant handling and running costs. But over the last ten years, research at many universities and research centers around the world has undergone a paradigm shift: agricultural robot automation is now considered crucial for increasing overall productivity and should be able to eliminate labor-intensive manual tasks, lower production costs, and improve the quality of fresh produce [14].

Nonetheless, a multitude of recent studies have demonstrated that agricultural robots are technically possible for a range of crops, agricultural tasks, and robotic characteristics [14]. However, automation solutions for field operations have not yet been effectively and extensively used in the commercial sector [15], and only a small number of recent innovations have been tested, adopted, and put into service. From an industrial standpoint, most of the processes were changed [16]. In the thirty years that have passed, a great deal of research on intelligent automation and agricultural robots has fallen short of the implementation stage. These failures were mostly caused by the planned systems' exorbitant cost, inability to carry out necessary agricultural labour, low durability, and inability to fulfil mechanical, economic, and/or industrial standards or to repeat the same tasks. Robot technology may be used in agriculture if a few conditions are met, as mentioned by [16] and [17], which are:

1) When compared to alternative methods, using robots is less expensive.
2) Robotics in agriculture increases productivity, yields, profitability, and survivability while improving the final output's quality and consistency.
3) Robotics reduces volatility and unpredictability in growth and manufacturing processes.
4) Robotics, as opposed to the traditional way, enables the farmer to make more accurate decisions and/or produce higher-quality results, which facilitates growth and production phase optimization.
5) The robot can perform jobs that humans would find hazardous or impossible to complete by hand.

This review focusses on the importance of overall and advanced robotic precision spraying, as well as current technologies, in the growing field of precision agriculture. Section II describes the precision agriculture market. The design and development of spray robot technologies, both on terrestrial and aerial platforms, are presented in Section III. Section IV describes the spray technologies and their spraying mechanisms. The different types of spraying techniques and the development of sensor technologies for precision spraying are presented in Sections V and VI. Section VII describes the state of the art and future challenges, and finally, the conclusion of the paper is discussed in Section VIII.

II. PRECISION AGRICULTURE MARKET

Precision agriculture is a technological approach to farming management that individually observes, measures, and analyses the needs of the fields and crops. Allowing the farmers to receive tailored care and to manage water efficiency effectively improves production, boosts economic efficiency, and reduces waste and environmental impact. The development of precision farming is shaped by two technological trends: advanced analytics capabilities and big data, robotics with sensors, and aerial imagery with sophisticated weather forecasts [18]. Globally, the precision market is valued at USD 8709.18 million in 2022 and is expected to reach a value of USD 21410.06 million by 2030 at a CAGR of 11.90% over the period [19]. The demand for food globally, extended profitability and crop yield, and crop health monitoring are the factors that are majorly driving the precision farming market. The growth in farm automation in developing countries and the dependency on the demand for food due to the increasing population are the critical factors that drive the growth of precision farming in the market and will continue to do so in the coming years. The growth in investment in technology, such as guidance systems, autonomous tractors, and GPS sensing systems, and the encouragement from the government are also factors in the growth of precision farming. The change in weather due to global warming is primarily the main factor in adopting advanced farming technology to increase productivity. It is expected to enhance the growth of the precision farming market in the upcoming years. Figure 1 provides an overview of precision delivery in agricultural robotics, illustrating its motivational background and outlining future trends.

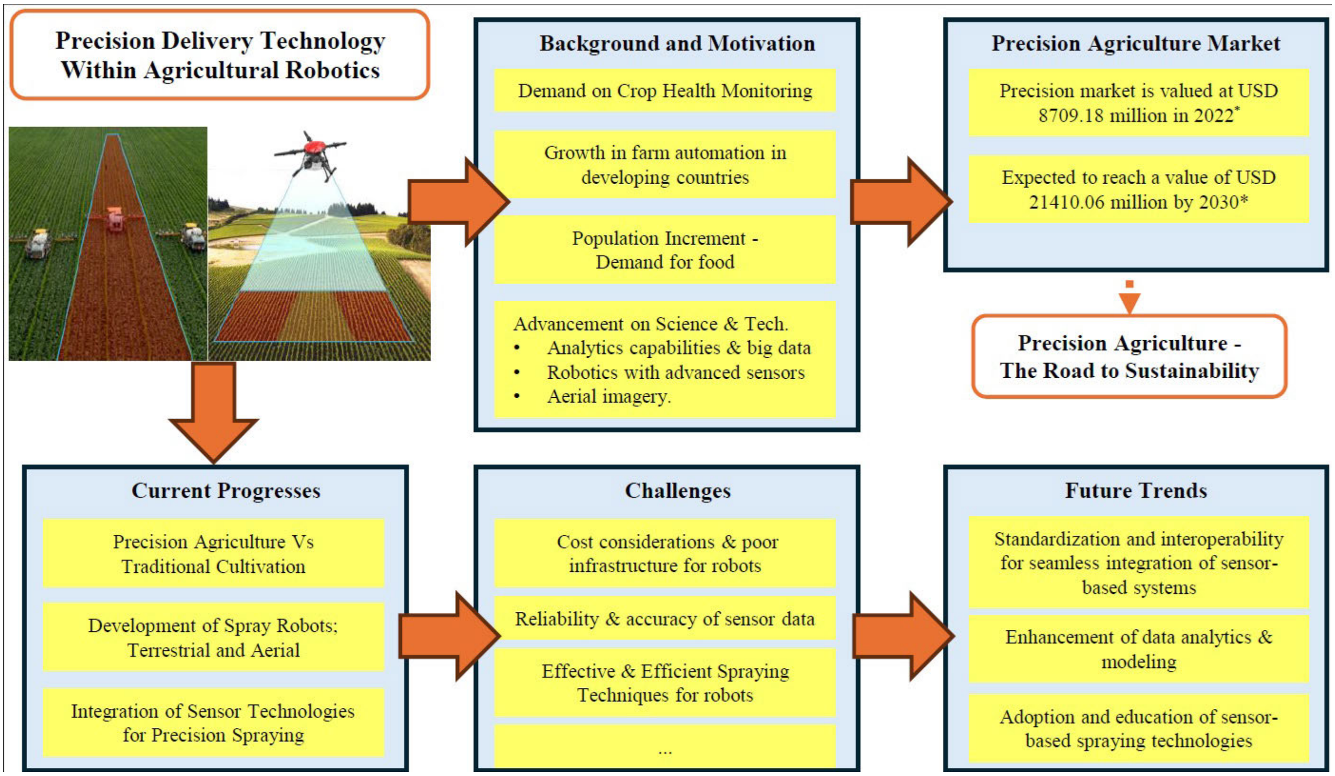

FIGURE 1. Overview of precision delivery of agricultural robotics.

TABLE 1. Big data and advanced analytics (BDAA) is real opportunity to tackle multiple challenges faced by the upstream steps of the value chain [18].

Opportunity	Industry challenge	How BDAA can help (examples)
Win the innovation game	High need for innovation, particularly in inputs at speed	Building a "data innovation engine" using insights from millions of trials to find the "product per PL"
Optimize farming operation	50% more and better food needed over next 20-30 years	"Precision agriculture" based on measuring and optimizing granular field operation
Increase supply chain transparency	Currently little foresight into crop volumes. High price volatility	Increasing forecasting accuracy with real-time data collection and analysis. Integrated planning across the value chain for lowering response time, risks
step up downstream operations	Ag processing is a high-volume, huge business with low operational efficiency	"Operations big-data toolbox" - production optimization, e.g., holistic, simulation-based plant optimization, predictive maintenance
Tackle the infrastructure challenge	Poor infrastructure in emerging markets, particularly Africa	Advanced analytics to identify key bottlenecks in infrastructure (e.g., car/truck monitoring). Infrastructure network optimization, e.g, warehouse location based on geospatial data/models
Anticipate waste	Enormous amounts of residential (food) waste (Upto to 30% of some crops)	Granular data collection of waste streams in households, etc., as a basis for e.g., Changed offerings in retail and regulation and public services.

According to delivery method, application, and service provider, the precision farming industry is segmented [19]. The delivery model study separates the market into two categories: cloud-based and local/web-based. It is divided into categories such as yield monitoring, crop scouting, field mapping, inventory management, weather tracking and forecasting, farm labour management, financial management, and so forth at the application level. The market is segmented into system integrators, managed services providers, aided professional services providers, connection service providers, maintenance, software update, and support services providers based on the service provider.

Also, the growing adoption of advanced high-end technologies is anticipated to support the growth of the growing market in a limited time frame. Although there is a high capital investment, the lack of standardization in the precision farming industry is expected to hamper the market's growth in the coming years. However, integrating agriculture hardware and smartphones and software applications like big data and artificial intelligence are expected to draw immense opportunities for the market [20].

1) PRECISION AGRICULTURE - THE ROAD TO SUSTAINABILITY

Using precision agriculture, farmers can achieve the following:

- Determine which hybrid seeds and crops are best suited for a given region.

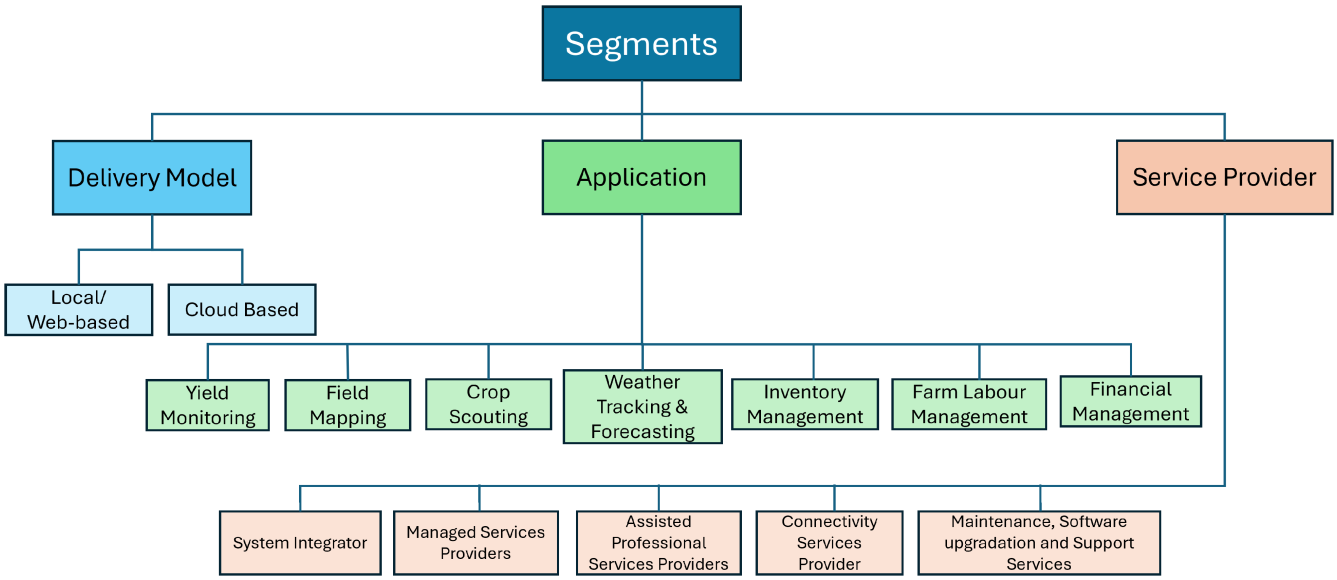

FIGURE 2. Precision farming market size.

- Only performs work on precisely designated replanting areas. Implement targeted measures to supply the necessary and ideal quantity of inputs (chemicals and fertilizers).
- Reduce the environmental damage caused by soil and water pollution while saving time and money.
- Make irrigation schedule maps, apply the right amount of water to the soil, and irrigate the item.
- Take precautions against diseases and pest infestations in advance of their destructive effects on crops.
- Use insecticides and weed killers without destroying non-target plants or endangering biodiversity.
- Harvest produces early enough to allow for longer storage times and when it is mature enough to satisfy consumer preferences.

Site-Specific Crop Management (SSCM), also known as precision agriculture (PA), is defined as a technology-enabled farming management method that monitors, assesses, and evaluates the requirements of the specific fields and crops [21]. Precision agriculture's primary objectives are to boost output and efficiency while lowering input costs and enhancing environmental sustainability. Precision delivery dates back to the initial GPS (Global Positioning System) satellite launches in the 1950s and 1960s.

A. PRECISION AGRICULTURE VS TRADITIONAL CULTIVATION

There are significant differences between the two practices. In traditional agriculture, farmers use the same quantity of fertiliser and insecticides on their fields, and they water them at the designated times and intervals in accordance with local regulations. A single farmland's biological, physical, and chemical characteristics always vary, even when the same amount of pesticides and fertilisers is applied. When inputs are treated in this way without taking into account their intrinsic differences, fertile land tends to misuse them, whereas impoverished patches receive less utilisation. The cost and environmental effect are increased by this inefficient use of fuel, land, water, fertilisers, and pesticides [21]. Conversely, precision agriculture uses Variable Rate Application (VRA) to optimise input by channelling it towards the unique characteristics of the farmland. In order to execute the VRA, comprehensive spatial data must be gathered throughout agricultural fields and locations using remote sensing and GPS to track crop life cycles [21] and information systems like Geographic Information Systems (GIS). However, precision agriculture uses variable farming to target the variations in the field inherently.

III. DESIGN AND DEVELOPMENT OF SPRAY ROBOTS

The advancement of robotics and its innovation in agriculture continue to be widely used in most agricultural production worldwide. These robots can be seen in almost all the agriculture industrial processes such as seeding and planting, nurturing, harvesting, and processing [54], [55], [56], [57], [58]. The development and deployment of such robots can be observed in various vicinities, including open fields, facilities, greenhouses, and orchards, where a diverse range of plants are cultivated.

The conditions of agricultural production are rather complex and require precise operation and maneuverability, which are expected to be performed by these robots. As a result, these robots are typically manufactured with specialized components designed to perform specific functions and tasks. These components include vision, control, mechanical, and navigation systems, which are the foundational elements

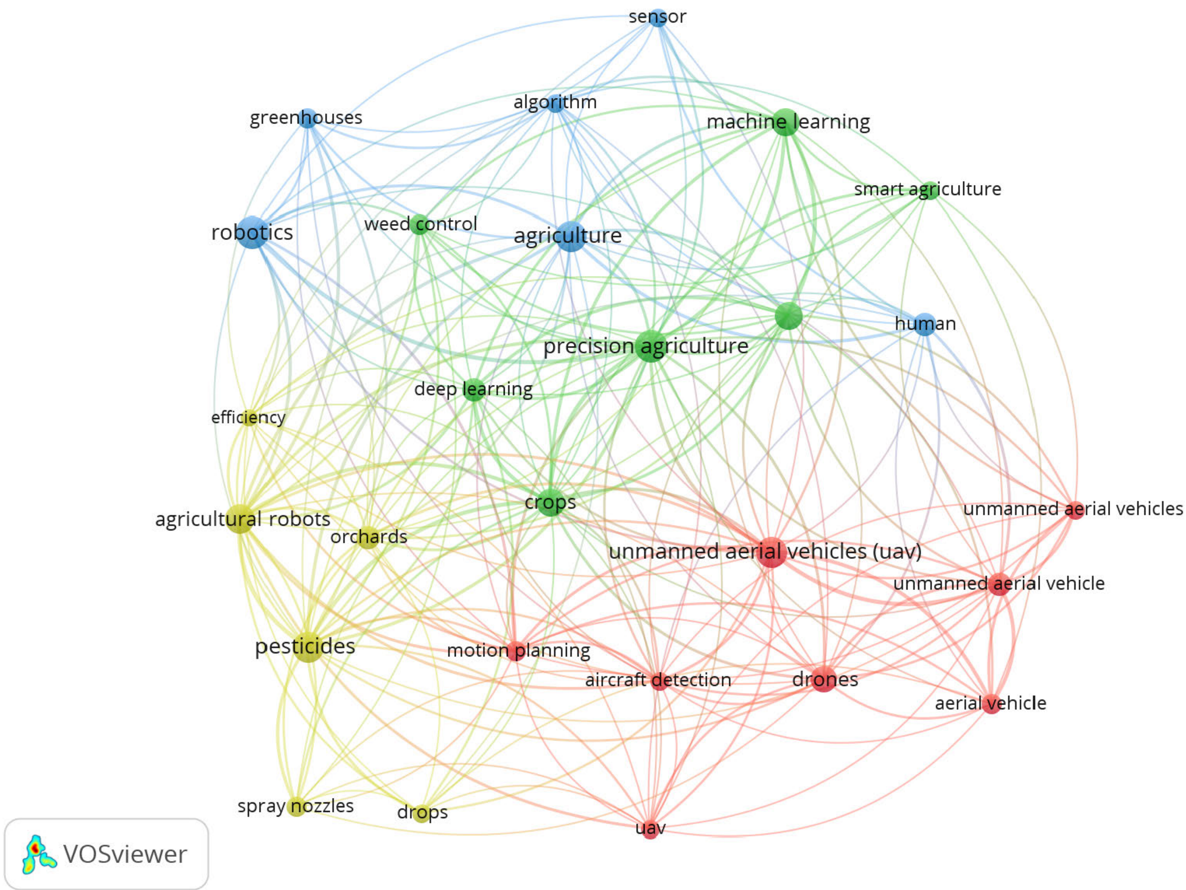

FIGURE 3. Visualization of related keywords in precision agriculture.

FIGURE 4. University involved in research relating precision agriculture-related works from 2014 until 2024.

of agricultural robots and are commonly studied in research. With these components, the robots are expected to navigate, avoid obstacles, perform detection, and carry out specific tasks as described in [59], [60], [61], [62], and [63].

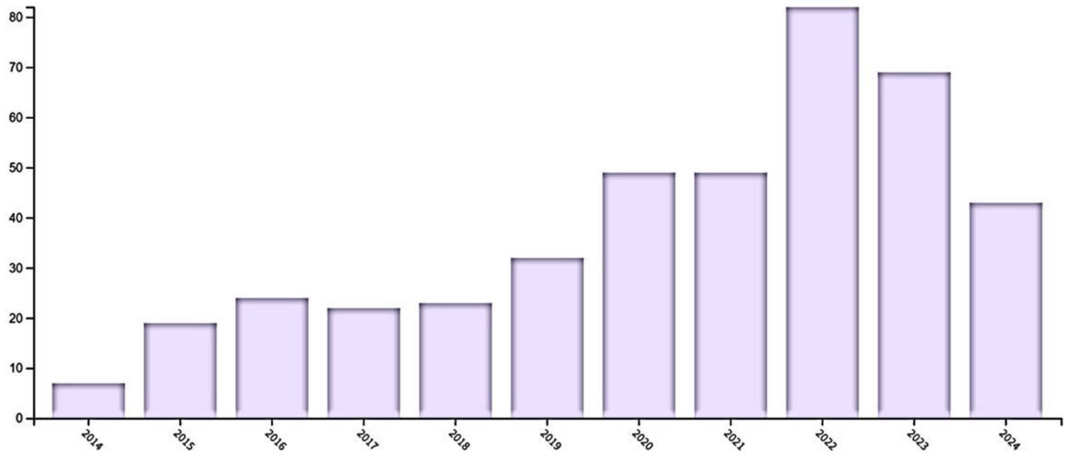

FIGURE 5. Publication and citation on precision agriculture-related works from 2013 until 2024.

In a broader scope, agricultural robots are generally categorized into two main applications: (i) terrestrial and (ii) aerial. As mentioned by [64], the main difference in this application is that in terrestrial applications, the robot must follow a path within the crop field and primarily relies on ground vehicles. These vehicles need to maintain constant contact with the ground to move effectively. Further, these agricultural robots can be categorized based on their operational setup (manned or unmanned) and mode (manual, semi-autonomous, autonomous). Table 2 summarizes the overview of the precision delivery for agricultural robotics.

The following section will discuss aerial and terrestrial spray robot design and development.

A. AERIAL SPRAYING ROBOT

Aerial spraying robots spread in various setups and model based on their operational setup (manned or unmanned), mode (manual, semi, autonomous), and wing type (rotary, fixed-wing, hybrid). The first application of such robots came from an increasing number of practitioners who use manned and manually controlled aircraft with spraying systems for pesticide applications instead of land vehicles. The aircraft should have adequate sensors and devices to deploy such an aircraft setup for spraying. In [65], Antuniassi et al. explore using aircraft equipped with multiple devices that allow the pilot to cross-check information while in flight. In a similar setup, [65] outlines the principles required for the implementation of Micro-electro-mechanical System (MEMS)-based Inertial Measurement Units (IMU) navigation systems to guarantee the correctness of the data supplied to pilots. The primary goal of this system is to provide the pilot with a more precise understanding of the aircraft's location than is possible when using other options, including the Global Positioning System (GPS).

While manned aircraft can effectively perform spraying tasks in the agricultural sector, it should be noted that manned operations are prone to human error, and the pilot's expertise and skill level significantly play a crucial role in achieving this goal. Further, the maneuver that the pilot decides may impact the quality of pesticide spraying from the air, regardless of the system's validation [64]. Therefore, the following subsections emphasize the design and development of unmanned aerial spray robots for further discussion.

1) TYPES OF AERIAL ROBOTS FOR AGRICULTURE

Recall that aerial robots can be categorized based on their operational setup (manned or unmanned), mode (manual, semi-autonomous, autonomous), and wing type (rotary, fixed-wing, hybrid). Specifically, the appearance and configuration of aerial robots vary significantly based on their wing types. This section summarizes the different types of aerial unmanned robots, commonly known as drones, focusing on their wing configurations.

- Rotary wing drones, an aerial robot, resemble helicopters with several rotors and blades, as illustrated in Figure 6(a). The most popular configurations feature four rotors (quadcopters) or six rotors. These drones are simpler to maneuver than their fixed-wing counterparts, as they can take off and land vertically without needing landing strips. Additionally, rotary-wing drones are generally more cost-effective than fixed-wing drones.
- Fixed-Wing Drones: As shown in Figure 6(b), a fixed-wing drone typically has one or two propellers and wings similar to an airplane. Compared to rotary-wing drones, this drone has a longer flight duration. Large farms today can benefit from long flight times. However, they are more challenging to operate than copters and require a smooth strip for takeoff and landing.
- Hybrid Drones: Hybrid drones can transition from vertical takeoff to a gliding mode while in the air. Thus, they incorporate the benefits of the other two types of drones. The longer flying time of a fixed-wing drone and the simplicity of operation of a rotary-wing type are promised by hybrid drones. Hybrid drones, however, are

TABLE 2. Overview of the precision delivery for agricultural robotics.

Platform	Components	Vicinity	Plant	Mode	Reference
Quadcopter	Control	Open Field	Not Specified	Autonomous	[22]
	Navigation		Not Specified	Autonomous	[23]
	Control, Vision		Not Specified	Manual	[24]
	Navigation	Simulated	Not Specified	Autonomous	[25]
	Control, Vision	Open Field	Not Specified	Semi	[26]
	Vision		Strawberry	Semi	[27]
	Control, Navigation		Not Specified	Autonomous	[28]
	Control, Navigation	Simulated	Not Specified	Autonomous	[29]
3 wheel	Navigation	Facility	Not Specified	Autonomous	[30]
4 wheel	Navigation	Open Field	Not Specified	Semi	[31]
	Navigation		Not Specified	Semi	[32]
	Mechanic	Facility	Artificial Tomato	Manual	[33]
	Mechanic	Open Field	Canadian poplar	Manual	[34]
	Navigation, Vision		Wheat	Autonomous	[35]
	Mechanic		Pistachio	Manual	[36]
	Mechanic, Navigation	Facility	Not Specified	Semi	[37]
	Navigation, Vision	Simulated	Not Specified	Autonomous	[25]
	Mechanic, Vision	Open Field	Anthurium	Semi	[38]
	Control, Navigation	Simulated	Not Specified	Not Specified	[39]
	Control, Navigation	Simulated	Not Specified	Not Specified	[40]
	Mechanic, Vision	Open Field	Not Specified	Semi	[41]
	Navigation, Vision	Facility	Not Specified	Autonomous	[42]
	Vision	Orchid	Grape	Semi	[43]
	Navigation, Vision	Facility	Not Specified	Autonomous	[44]
	Mechanic	Facility	Not Specified	Manual	[45]
	Mechanic, Vision	Facility	Grape	Semi	[46]
	Navigation, Vision	Orchid	Not Specified	Autonomous	[47]
	Navigation	Open Field	Not Specified	Semi	[48]
Hanging track	Navigation, Mechanic	Facility	Cucumber	Autonomous	[49]
Rail System	Control, Mechanic	Orchid	Canopy tree	Semi	[50]
	Mechanic, Vision	Facility	Not Specified	Manual	[51]
Tracked wheel	Control, Vision	Orchid	Grape	Autonomous	[52]
	Mechanic	Facility	Tomato	Autonomous	[53]

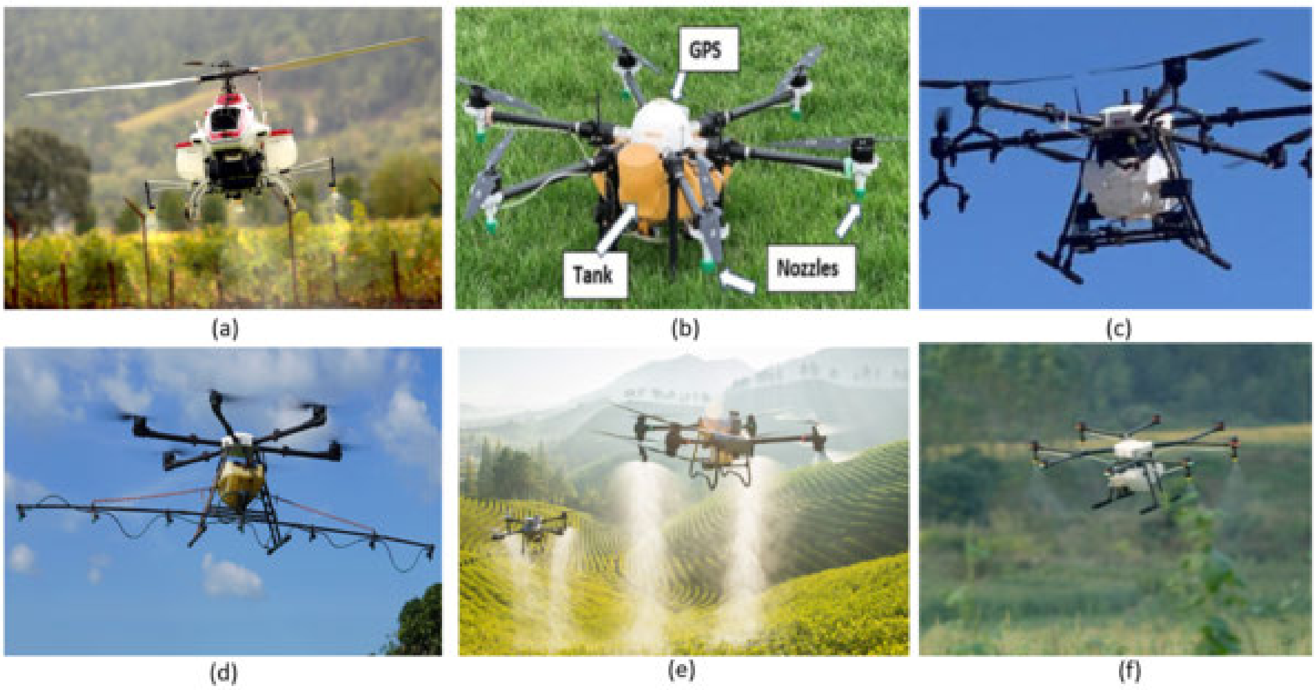

FIGURE 6. Some examples of targeted spraying drones (a) Yamaha RMAX drone, (b) Spray drone with no boom, (c) Spray drone with boom, (d) Spray drone with an extended boom, (e) DJI AGRAS T50, (f) DJI Agras MG-1.

more costly, heavier, and sophisticated. Similar to the other two categories, technology is less developed.

A further discussion on the difference between such drones is presented in [66]. It is noted that using fixed-wing aircraft

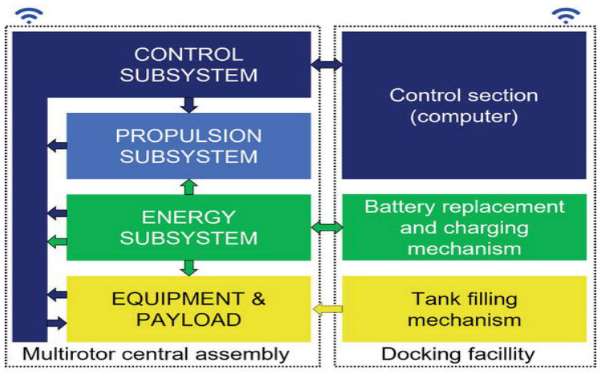

FIGURE 7. Concept representation of aerial robotic system.

to spray pesticides shows environmental preservation issues due to the executive drift of pesticides, which can affect neighboring areas. Consequently, other works have studied safer and more accurate alternatives for pesticide spraying using rotary wing drones in [66], [67], [68], and [69]. A detailed discussion is provided by [70], which explores the reason for such a phenomenon. According to [70], one of the main causes of such environmental issues is because these aircraft operate without pilots, which makes the plantation the target of their downwash effect. This downwash can shield the sprayed pesticides from the elements. Utilizing this effect, some researchers have proposed applying pesticides to agricultural fields using an unmanned helicopter equipped with a spray system, as suggested by [69].

2) UAV INTEGRATION

Considering the various operational setups, UAVs have been integrated and deployed in several sectors to promote digital agriculture. These applications include field scouting sector [71], precision management of oil palm plantations [58], [72], estimation of plant metrics including height and leaf area index [73], health evaluation [74], and variable rate spraying [75], [76]. Their uses can also encompass crop fertilization, seed planting, and related tasks [77]. A multirotor UAV can carry out missions including the precise application of pesticides, considering the crop's characteristics, the degree of disease or insect infestation, the site, and additional factors [78]. Further integration of the UAV in the precision delivery sector can be seen in [79], [80], and [81]. Reference [79] propose a novel aerial electrostatic spraying using UAV where [80], [81] develop a UAV-based automated aerial spraying systems. An interesting work by [82] involves designing an embedded real-time UAV spraying control system with onboard image processing built on inexpensive hardware.

Several works have focused on proposing algorithmic approaches to integrate UAVs for such tasks. Reference [29] present an algorithmic control approach for autonomous UAV swarm spraying. The authors highlight the capability of computer-controlled UAVs for crop spraying, which allows for nonuniform coverage with high precision and time efficiency. Further, the study [68] proposes an algorithm to adjust the UAV route in response to wind intensity and direction changes. The motivation behind this study is based on various related work that limits meteorological conditions that vary suddenly, such as abrupt changes in wind direction or speed. In a similar setup, an adaptive method for UAV-based pesticide spraying in dynamic situations is given in the paper [23].

Additional technical challenges emerge when UAV integrates into the precision delivery scene, such as droplet size and windward airflow on the motion of droplet groups. This is because the exact control of droplet deposition on the target and the mitigation of ambient pollution are critical components of the mission. To address this issue, there is a study on computational fluid dynamics and a numerical simulation of spray drift movement using multirotor UAV. Further, [83] presents a variable spray system, which can quickly alter the nozzle's flow range. According to the experiment, the dispersion of droplets is the main issue with smart spraying with drones, and numerous academic studies have been written about it. Further, the work concludes that the equipment and payload, electric energy, electric propulsion, and control subsystems are the four subsystems that make up the aircraft system.

To summarize, integrating UAVs into the precision delivery sector requires consideration of various parameters and technical aspects. These include spraying height, flight speed, nozzle flow rate, the number and orientation of nozzles, and other components of the UAV system. The following subsection presents a detailed discussion on these technical aspects, focusing on flying route or coverage path planning and sprinkler modeling.

3) SLOSH DYNAMICS IN UAVS

Slosh dynamics refers to the movement of liquid (in this example, insecticides) through the UAV's tank as it flies. This movement can generate unstable forces and moments, which may have an impact on the UAV's flying stability, control, and spraying accuracy. Slosh dynamics research on unmanned aerial vehicles (UAVs) for pesticide spraying is becoming increasingly important, owing to the challenges given by liquid movement within the UAV's tank during flight. Understanding and addressing slosh dynamics can improve the stability, efficiency, and safety of UAV operations, particularly during flight manoeuvres and spraying activities. Slosh dynamics can cause instability in UAVs, especially during complex manoeuvres or at high speeds. A study on the longitudinal flight dynamics of UAVs revealed how liquid flow can impair the vehicle's equilibrium and control, highlighting the necessity for adaptive flight control systems that can adjust for these disturbances.

The efficiency of pesticide spraying with UAVs is highly related to the dynamics of the liquid in the tank. Research has demonstrated that flying velocity and UAV design, particularly rotor type, have a considerable impact on droplet deposition and drift. For example, higher flight velocities can help disperse pesticide droplets more effectively, but they may also lead to uneven distribution and increased drift. CFD simulations were used to study the behaviour of liquids in UAV tanks, allowing researchers to better understand how different UAV designs and flight conditions affect slosh dynamics. These simulations are crucial for optimising UAV designs to reduce the harmful consequences of sloshing. The findings from these investigations are directly useful to the development of more stable and efficient UAVs for agricultural applications. Manufacturers can design UAVs that apply pesticides more consistently, decreasing waste and environmental damage, by better understanding slosh dynamics. The slosh dynamics has an impact on the UAVs performance that includes:

- **Stability:** Sloshing can cause shifts in the UAV's centre of gravity, resulting in oscillations or instability, especially during spins, accelerations, or decelerations.
- **Control:** Unpredictable changes in liquid mass can make precise control of the UAV more difficult, causing navigation and pesticide application challenges.
- **Spraying Efficiency:** Irregular liquid movement can cause unpredictable spray patterns, resulting in uneven pesticide dispersion and lower efficacy.

Some investigates the behaviour of liquid sloshing in a partially filled container. The project focusses on creating and implementing a low-cost measurement system to precisely estimate slosh dynamics, which are crucial in a variety of applications including aerospace, automotive, and maritime industries. The study focusses on the issues given by sloshing, which can result in destabilising pressures and moments that impact the stability and control of vehicles carrying liquid loads. Overall, this study helps to develop cost-effective solutions for managing slosh dynamics, which has important implications for enhancing the safety and performance of liquid-transporting vehicles and systems.

The control components of UAVs for pesticide delivery are focused on maintaining stability and achieving exact application despite the difficulties provided by liquid sloshing. UAVs can achieve higher performance, longer endurance, and more efficient pesticide application by utilising tactics such as PID and LQR control, as well as potentially including adaptive control mechanisms, resulting in more effective and sustainable agricultural operations.

A comprehensive investigation of how control tactics might be used to increase the performance and endurance of UAVs carrying liquid payloads are also discussed in the literature. The study focusses on the issues provided by liquid sloshing within the tank during flight, which might impair the vehicle's stability and efficiency. A mathematical model of the UAV's behaviour, including the effects of liquid sloshing was developed. They then investigate the employment of Linear Quadratic Regulator (LQR) and Proportional-Integral-Derivative (PID) control techniques to counteract the destabilising effects of the sloshing liquid where liquid payload management is critical to vehicle success. The investigation of slosh dynamics in UAVs for pesticide spraying is critical to the improvement of precision agriculture. By solving the issues provided by slosh dynamics, UAVs can become more stable, efficient, and dependable, resulting in improved crop management and more sustainable agriculture methods.

4) COVERAGE PATH PLANNING OF THE SPRAYING DRONES

Autonomous disinfection before and during flight requires combining many methods into a single application. The first step is to simulate the sprinkler coverage. To define the ROI, the next step is to create a geodetic coordinate polygon. At that point, the unmanned aerial vehicle (UAV) is prepared for action. The flight mission is then scheduled. After that, the UAV must automatically lift off and follow the predefined path. More precisely, the mission planning determines a set of waypoints that will be loaded into the onboard controller using the ROI, the sprinkler model, and the vehicle's capabilities as input. With sprinkler modelling, the sprayer's coverage area is calculated from a set point. Coverage Path Planning (CPP), or selecting a vehicle path to guarantee that the ROI is covered, is the main priority at this planning stage [84]. Nonetheless, near-optimal pathways can be found using linear complexity algorithms by applying certain geometrical assumptions to the issue [85].

Further, proper sprinkler system modeling is necessary for disinfection planning; disinfection is compromised. Two approaches were discovered after the literature on CPP for UAVs and spraying UAVs was reviewed: (i) one that focused on finding a solution to the CPP problem for UAVs, and (ii) another that addressed the spraying task without taking the CPP problem into account. On the other hand, the first style is primarily focused on applications related to monitoring, avoiding obstacles, inspecting, mapping, and area reconnaissance. There were just four papers on the CPP issue that dealt with the work of spraying [86], [87], [88], [89].

A method for applying fertilizer and insecticides to open-crop fields was created by [86]. Manual flight plans were used to steer the spraying UAV. To identify green fields and the boundaries of the crop regions, the UAV was equipped with a camera to take remote-sensing pictures. QGIS software examined the remote sensing photos to create a region map.

Additionally, [90] described a way to break down non-convex polygons into convex areas to address the CPP problem and find a path that uses less battery power. The UAV is equipped with a camera to start. After that, it takes pictures from the ROI. Subsequently, the algorithm generates a zigzag or back-and-forth motion to accomplish the polygon coverage. It uses the overlap and the camera footprint to calculate the distances between two straight motions. Lastly, it provides a route with the fewest UAV turns possible.

For a UAV equipped with a camera, [91] concatenated G^2 curves to create G^2 viable pathways that would allow for persistent surveillance flights. A cycle sequence was found for the surveillance ROI using an augmented A* algorithm. The purpose of this sequence was to create smooth pathways that meet curvature restrictions using a B-spline curve generation technique. An algorithm for path planning based on continuously updating the virtual regional field and its local gradients was proposed by [92] for the same problem. This virtual field included a boolean function to create a logical map that holds the data about the targets and obstacles.

A multirotor UAV autonomous aerial system that navigates across an orchard to inspect crops was also introduced by [93]. Yield data from the ROI was gathered using a stereo camera. UAV navigation, vision-based obstacle detection and avoidance, and CPP components were created for this. When navigating to the next tree, the autonomous aerial system includes a local planner in addition to using a global planner for entry and exit.

Additionally, a strategy for solving CPP for accurate spraying in peach orchards was proposed by [93]. To do so, video images were captured using a binocular color depth sensor. Subsequently, a technique for segmenting color-depth fusion images that relied on the leaf wall region was suggested. Furthermore, the two most excellent leaf wall sections were identified as an ROI using image erosion. The trajectory of the UAV that sprayed was determined by designating the middle of the ROI spacing as the spray path's end.

For their part, [94] suggested a path planner for rotating calipers that computes the entire path to cover a convex ROI from a 2D perspective for precision agriculture or disaster management. Throughout the mission, the drone's pinhole camera captured images of the ROI. The method repeatedly adds waypoints by drawing a line intersecting the ROI polygon. The process needs the polygon, a beginning vertex, an adjacent vertex, an antipodal vertex, and the separation between flight lines. [88] used multi-quadcopters to offer a mission assignment strategy for the farmland spraying problem. An algorithmic quadratic programming technique was applied to find the best answer, and a mathematical model for the mission assignment was utilized to solve the problem. Therefore, pesticides can be sprayed by quadcopters on farms, but they cannot be sprayed on regions that are covered by other quadcopters. The Inspection Path Planning Problem was formulated by [95] as an expanded Traveling Salesman Problem (TSP) for a UAV. To overcome the issue, they presented the discrete particle swarm optimization (DPSO) technique, which combines edge exchange, random mutation, and deterministic initialization. Using its CCD camera, the UAV can identify potential problems or flaws in the scanned area and determine the quickest route for inspecting the planar surface. They employed parallel computing for the particles' aptitude, location, and velocity. Using the MAVLink protocol, the parallel program was executed on a Jetson board mounted to the UAV. Furthermore, a CPP approach based on the rural postman problem was presented by [94] to solve discontinuous areas. The issue was fixed by calculating the back-and-forth pattern and optimizing the visitation sequence. They solved the problem by applying a genetic algorithm after converting the convex polygon into a reduced graph and treating it as the TSP. To determine the back-and-forth pattern, they sorted the polygons and the set of vertices using their planner's suggested order.

To reduce coverage time and maximize coverage area for UAV-based intelligence, surveillance, and reconnaissance missions, [96] developed a linear programming model. During the first phase, a mission planner identified each UAV's search pattern, point of interest (POI), and ROI. The mission planner allocates specific ROIs and flight paths to every UAV involved in the mission during the second phase. Finally, the branch-and-bound approach in the CPLEX solver is used to solve the aggregated mixed-integer linear programming for the path planning problem. To create an aerial inspection path that maximized the quality of the recorded photographs and the coverage of a 3D surface while lowering the computational complexity of the solver, [97] proposed a co-optimal CPP technique. The method discovered viable routes for total visual coverage. A PSO that combined the effectiveness and quality of a coverage path into an objective function later included a set of the sampled paths. Next, using the randomly generated tree to explore quickly, the computed path was converted to a flight trajectory, avoiding obstructions.

A navigation solution was proposed by [98] for UAVs operating in tandem. The UAVs were mobile base stations that completed the coverage task, flew around a region of interest (ROI), and supplied data services to several ground-point locations. To prevent isolation inside the network, every UAV has to stay in communication with at least one other UAV. Next, a reinforcement learning-based framework was implemented to manage every UAV using environment state data. The UAVs were trained to maximize coverage for each vehicle, maximize the geographical fairness of all service points or points of interest that were taken into consideration, and minimize overall power consumption without ever leaving the area's perimeter through a reward function.

However, the following introduces studies on UAV spraying that do not consider CPP. To apply crop protection agents to designated growth zones signaled to the UAV by GPS coordinates or pre-programmed locations, [69] designed a low-volume spraying UAV. A comparable technique was developed by [99] to spray herbicides in fields and highland areas. A system that connected a water pump to a fertilizer tank monitored by a sensor was introduced by [100] for use in agricultural areas. The user was prompted to replenish the tank after reaching a certain threshold. [101] developed a system using a UAV (Quadcopter) with open-source autopilot software and a LIDAR sensor to clean the windows of high-rise buildings. The windows were cleaned using a microfiber brush, and the drone sprayed the water. Reference [102]

TABLE 3. Main features of commercial sprinklers.

Platform	Sprinkler Flatform	Features
Hexacopter	Sprinkler SS600 Commercial Agriculture	23 L tank. Covers up to 10 Ha/h. Integrate 4 nozzles. Flight time: 15-20 min. 6 rotors of 100KV. Weight: 46.5 Kg. Payload: 24 kg
Octocoper	Agras MG-1S Commercial agriculture	10 L tank. Covers up to 6 Ha/h. Integrates 4 nozzles. Flight time: 10-24 min. 4 rotors of 130 rpm. Weight: 8.0. Payload: 10 kg
Hexacopter	DJI Agras T16 Commercial Agriculture	16 L tank. Covers up to 10 Ha/h. Integrates 8 nozzles. Flight time: 10-18 min. 6 rotors of 75 rpm. Weight: 18.5 kg. Payload: 40.5 Kg
Hexacopter	DRONEHHEXA-AG Phytosanitary treatments	16 L tank. Covers up to 2 Ha/v. Integrates 4-8 nozzles. Flight time: 10-18 min. Weight: 12.4 kg. Payload: 32 kg
Hexacopter	Sprinkler GAIA 160AG Agriculture	22.5 L tank. Covers up to 10 Ha/h. Integrates 4 nozzles. Flight time: 18 min. 6 rotors of 100 KV. Weight: 24 kg. Payload: 46.5 kg

unveiled a UAV that uses a spray cannon to paint 3D surfaces in specific spots. The system is operated in a room where the user can move around and interact with virtual things using a virtual reality interface. Reference [103] sprayed insecticides on the sugarcane crop using a four-rotor drone. The spraying volume, height, and flight speed were the criteria that were taken into consideration. Finally, Table 1 describes a few trades spraying UAVs.

5) SPRINKLER MODELLING

Depending on the application and system parameters, a sprinkler system can be modeled in various ways [104]. In this work, we assume that the UAV has a single sprinkler installed and its height is rather low. The ceiling restricts the altitude in closed places; in open regions, the flight altitude should likewise be modest to avoid compromising the efficiency of the liquid. View Figure. 8 for an example of the model. Thus, we represent the coverage field kinematics of the sprinkler as a rigid body controlled by the following inverse paraboloid equations:

$$z = -Ax^2 - By^2 + h \tag{1}$$

If x and y are plane coordinates, h represents the drone's altitude, and parameters A and B specify the paraboloid's amplitude. Figure 3 presents the suggested model.

A model fitting can be done to deduce the parameters A and B using data from the drop's fall for a specific sprinkler, even though the marker frequently does not describe the sprinkler. The Levenberg–Marquardt Algorithm [105] is employed in this method to determine the paraboloid parameters (A, B). A fitted model for a specific collection of observed drops is displayed in Figure 9.

Drones confront a number of technical issues that can have an impact on their efficacy, reliability, and safety. The following are some of the major technological issues involved with spraying drones and its impact:

- **Slosh Dynamics:** It can cause uneven pesticide application and possible loss of control, particularly during curves or sudden accelerations.
- **Battery Life and Endurance:** Frequent recharging or battery changing is necessary, lowering efficiency and increasing downtime.
- **Payload Capacity:** Increased operational time and costs as a result of frequent refilling.
- **Spray Drift:** Pesticide application effectiveness is reduced, and there is a risk of environmental contamination, which will impact non-target crops and places.
- **Precision and Accuracy:** Inconsistent pesticide coverage, resulting in inefficient pest management and potentially excessive chemical use in specific areas.
- **Weather Sensitivity:** Due to operational limits and potential safety risks, spraying activities may be delayed or cancelled.

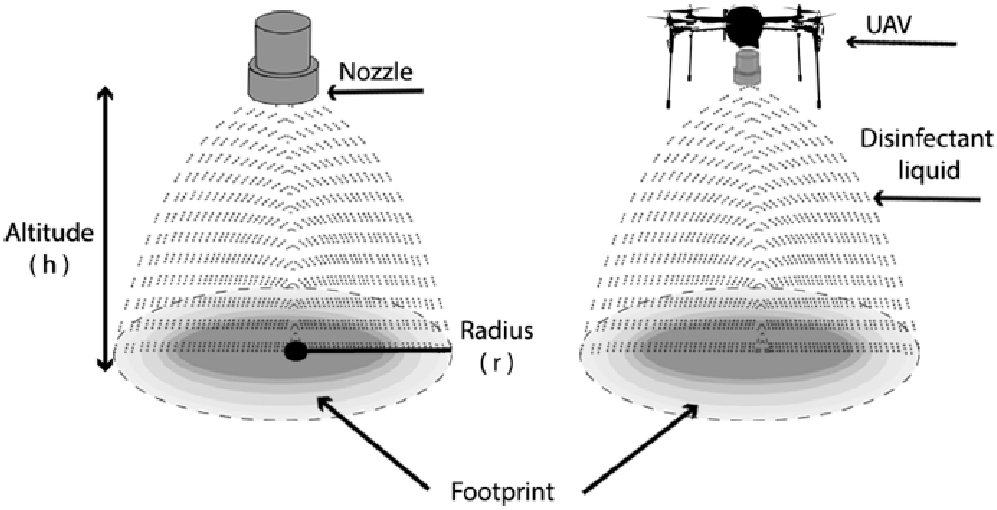

FIGURE 8. Paraboloid model of the disinfecting area. Given a UAV flying at altitude h, the footprint of the sprinkler is given by a circle of radius equal to r [25].

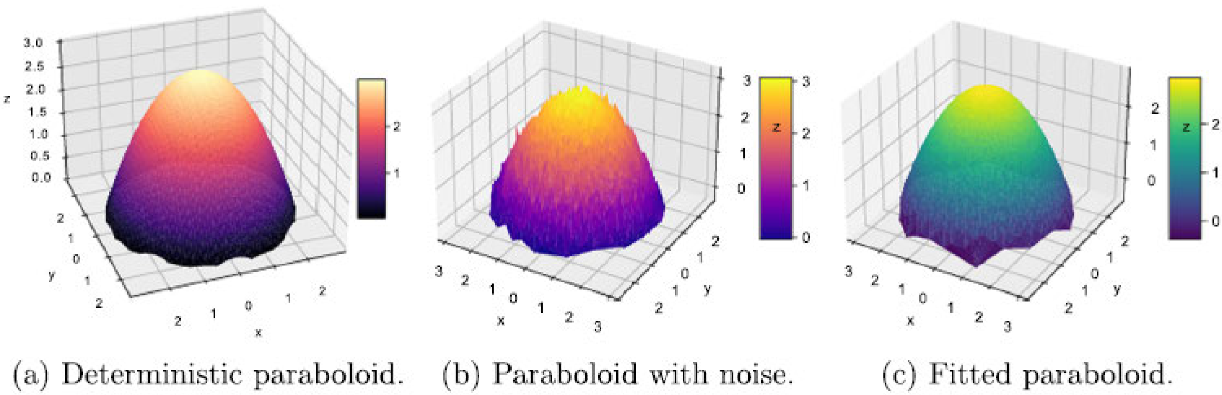

FIGURE 9. Sprinkler model based on paraboloid equations for a UAV at three meters. The paraboloid bounds the volume covered by the sprinkler. Units are in meters [25].

- **Navigation and Obstacle Avoidance:** To ensure safe navigation, advanced sensors and algorithms are required, which might raise the drone system's cost and complexity.
- **Regulatory Compliance:** Legal and operational issues that may limit drone deployment in specific areas or necessitate additional certifications and documentation.
- **Data Management and Integration:** The demand for advanced software solutions and data management systems, which might raise the cost and complexity of drone operations.
- **Maintenance and Durability:** Increased operational costs and probable downtime owing to frequent repair and maintenance requirements.

Addressing these technological problems is critical for improving the performance and efficiency of spraying drones in agriculture, guaranteeing that they can be utilised successfully and safely in a variety of farming applications.

B. TERRESTRIAL SPRAYING ROBOT - PLATFORM MOBILITY

The term terrestrial refers to the field of robots equipped with devices and sensors to perform spray in agricultural scenes. Similar to aerial robots, terrestrial robots can be categorized into various setups and models based on their operational setup (manned or unmanned), mode (manual, semi, autonomous), and wheel type (two, three, four, tracked, hanging track, rail system) as tabulated in 2.

1) TYPES OF TERRESTRIAL ROBOTS FOR AGRICULTURE

Terrestrial robots for agriculture can be widely spread in size and design based on their functionality. Some terrestrial robots are human-sized and can be deployed in narrow paths in some facilitated areas like greenhouses. Some can be as big as a truck with spray on the rear side to make the process smoother and better spraying coverage. It was determined to employ a medium-sized agricultural tractor due to the precision spraying system's requirements involving size, weight, and power, among other factors as in [106]. The vehicle was intended to be a system that would make it simple to connect or integrate different kinds of agricultural tools with the car to carry out a variety of agricultural chores, primarily (though not alone) weed control operations. The unmanned ground vehicle was outfitted with various cutting-edge perception and actuation systems to fulfill the demands of the site-specific spraying task. These systems included a real-time kinematic e-global positioning system (RTK e GPS) for precise localization, machine vision and laser for obstacle detection, and specialized sensors and actuators for tractor automation. Some of the different types of terrestrial robots are shown in Figure 10, Figure 11 and Figure 12. A hybrid architecture was used to control the unmanned ground vehicle. A Main Controller is responsible for receiving and carrying out missions generated by external operators, planning the appropriate actions that the vehicle and its implementation must carry out based on the mission requirements, and coordinating with the other subsystems onboard the vehicle.

Many crop production operations can be completed mechanically or semi-automatically by these design variations. A large number of these land-based robots are engineered to move about on wheels. The application of wheeled robots for pesticide spraying-based crop protection will be the main topic of this section. An autonomous pesticide sprayer with obstacle avoidance capability was created and used in [110] to spray pesticides precisely. Numerous crops, such as tomatoes, pineapples, and rock melons, can be used in this way. On the other hand, a lot of research was also done on the spraying pressure, waterproof construction, and modernising monitoring systems. Reference [63] created a vehicle and a spraying control system to form an autonomous spraying robot. The purpose of the development tests was to demonstrate that the two components could perform spraying activities more quickly and precisely. In order to achieve greater quality and productivity, [111] developed a semi-autonomous robot that could climb areca nut trees and then spray insecticide using a servo-controlled nozzle. This resolves the issue of human participation in constraints. In order to mitigate pesticide usage, [46] created a modular agricultural robot that can do autonomous disease detection and selected pesticide spraying. It is also the first completely automated robot system for spraying pesticides selectively on targeted crops.

There are some noticeable technical challenges in the design and development of terrestrial spraying robots. Regarding placing the spraying apparatus, it is necessary to place it close to the culture to minimise pesticide drift into nearby areas. On the other hand, spraying from above makes it possible to do so more quickly and does not require creating pathways within the crop area [64]. However, note that there is a greater risk of pesticide drift to nearby areas due to the greater distance between the spraying apparatus and the planted area. It's crucial to note that most aerial spraying happens very close to the ground, at only three meters above the ground, which raises the possibility of mishaps. In [112] proposed a flow control system for the smart spraying robot using semantic segmentation. Hence, contrastive field experiments were carried out to demonstrate the designed control systems exhibited better performance than the existing approaches. This section explores and analyzes robotic systems used for agricultural pesticide spraying. Creating these pesticides can help with the smart farm's diseased plant movement of necessary pesticides, plant disease identification, and application of the appropriate pesticide. This review shows every intelligent robotic pesticide spraying technology over the last 20 years. The robotic system consists of a spraying and disease detection system, aerial vehicles, and a serial manipulator mounted on a tracked ground vehicle. Typically, SOLIDWORKS modeling software is used to develop and assemble the tracked vehicle, spraying system, and models of the concepts being presented. In agriculture, chemical products are frequently used in the spraying process. These treatments, although successful, leave behind contaminants in the soil that lower plant variety and soil fertility [63]. As discussed in [52] suggests a three-part standalone sprayer set with height adjustment and separate control for the fan, atomizer, and nozzle (pump). Because they are maintained independently, the system may attain high accuracy, avoid losses, and function more efficiently. The AgIoT module and the PRYSM sprayer were assembled on the PRYSM robot. [113] developed a robotic sprayer for ground vehicles. The Swiss company ecoRobotix developed the AVO robot sprayer, which is used to provide fields with the required pesticides. The Trektor hybrid robot, created by the French business Sitia, is the next example of a distinctive machine. The second innovative gadget is a robotic platform developed at Moscow's Michurinsk State University with the goal of protecting greenhouse crops against environmental illnesses. A precise real-time target spraying system based on machine vision is examined for the field scene, and [37] created deep learning-based object identification technology for precision spraying. The overall architecture of the system is first proposed and comprises components for pressure-stabilized pesticide delivery, electronically controlled spraying, and image capture and detection. The results of the experiments show how successful the planned system is when put into practice. It can effectively minimize the amount of pesticides used, raise the rate at which they are applied, and lessen the environmental contamination of farms. This has certain effects on ecological preservation and agriculture productivity intelligence. In order to meet different needs for spraying in agricultural production [41]. Using the plant protection equipment already in place, a patch spraying-to-plant robot system was designed. Electric cylinders are incorporated into the robotic system to drive the suspension and modify height in order to meet different operational requirements.

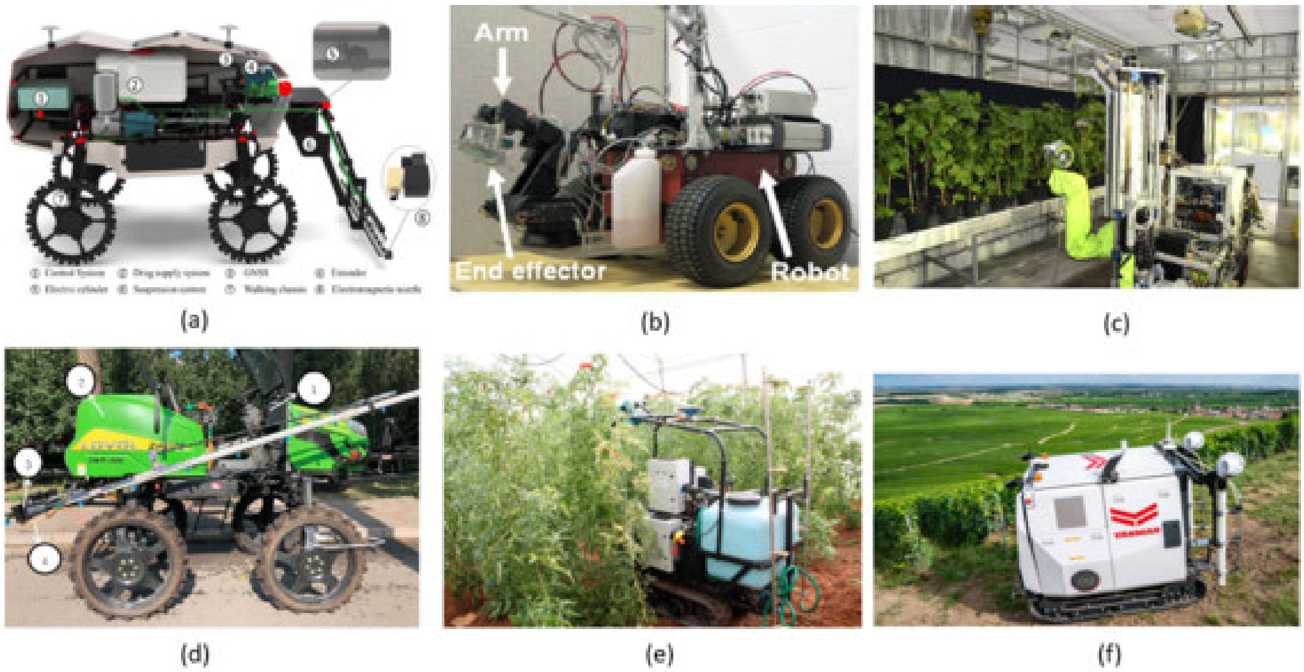

FIGURE 10. Some examples of robot platforms for different suitable applications (a) Patch sprayer ground robot, (b) Weed control robot platform, (c) CROPS modular robot, (d) High clearance Tractor platform, (e) Spray robot, (f) Yanmar's Revolutionary YV01.

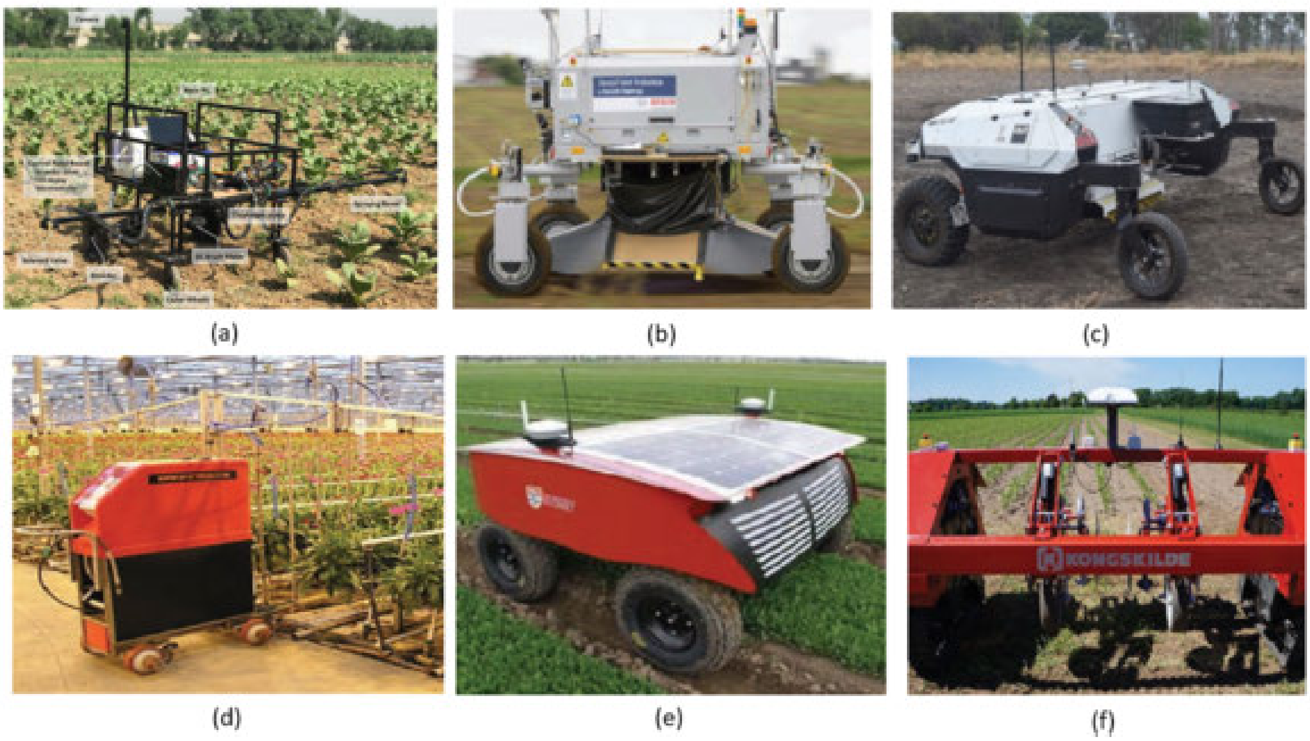

FIGURE 11. Some examples of targeted spraying robots (a) Spraying robot, (b) BoniRob, (c) AgBot II, (d) Spray robot, (e) RIPPA, (f) Kongskilde Robotti.

An electrical drive powers the platform. Figure 14 displays the platform's basic characteristics. The combined control mode of continuously matching real-time robot displacement and operational prescription map is used by the nozzle control strategy [41]. The initial introduction of the Aurora mobile robot for spraying activities was made by [38]. Reference [114] used optical equipment for automated controlling systems using red-colored target boards in order

FIGURE 12. Some examples of targeted spraying robots (a) Autonome Roboter, (b) Hortibot, (c) Crawler type robot platform, (d) Solinftec Solix Sprayer robot - Four wheel, (e) Electric sprayer wheel robot, (f) Robokheti 8 MegaPixel Autonomous Spray Robot.

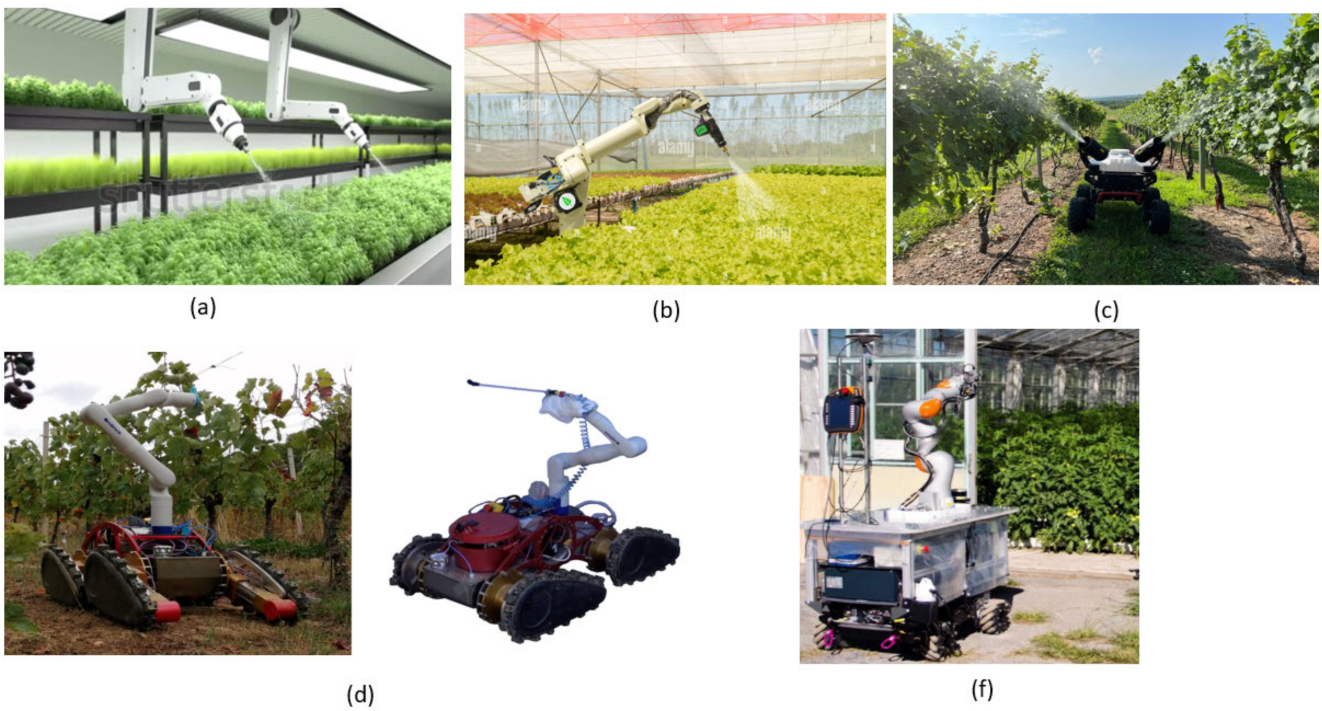

FIGURE 13. Some examples of robots with manipulator for spraying (a) Smart robotic farmer spraying fertilizer on vegetable, (b) Smart robotic in agriculture futuristic concept for spraying, (c) Robokheti 8 MegaPixel Autonomous spray Robot, (d) Mobile manipulator performing a spraying experiment in a vineyard and (e) Spot spraying robot with disease area detection.

to steer electric sprayers. In [63] study, vineyards and greenhouses were sprayed using a self-propelled sprayer robot. Reference [115] developed a robot that can identify and eradicate weeds from agricultural areas. One technique

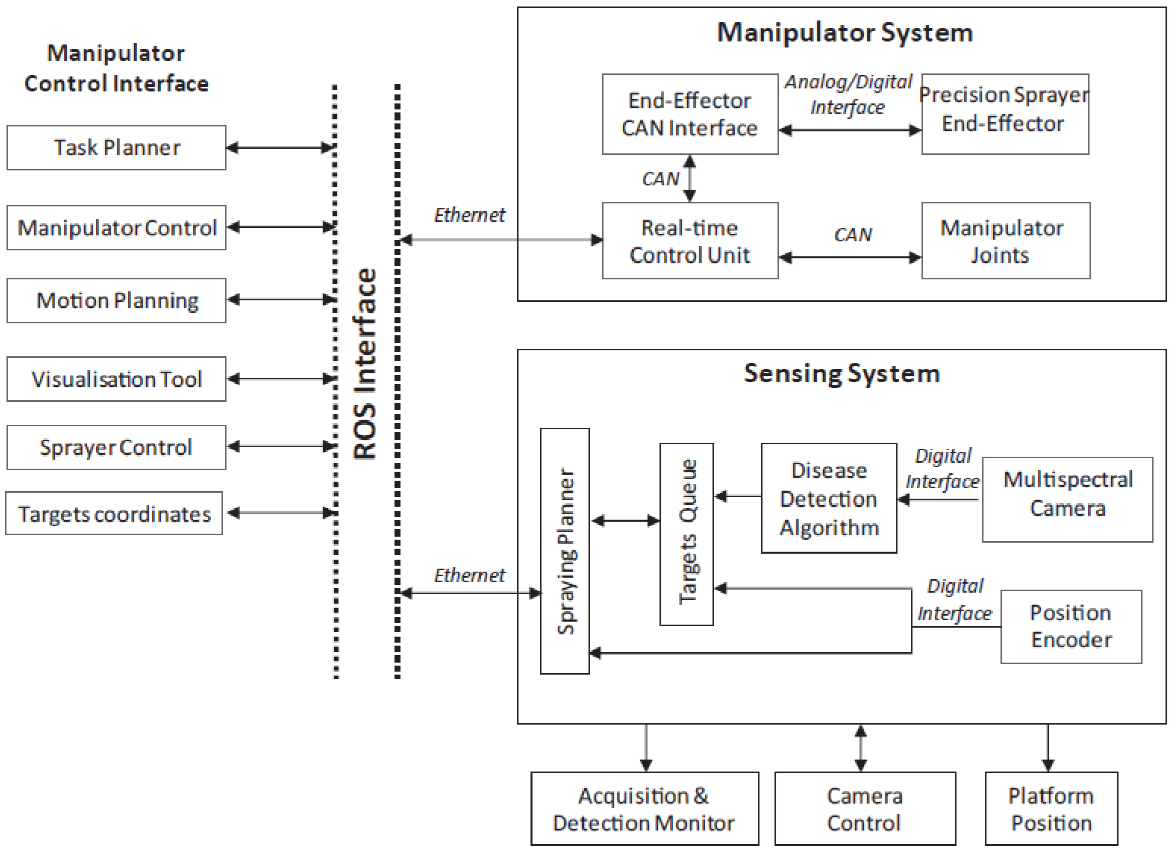

FIGURE 14. Schematic diagram of the manipulation system for the robotic spray delivery.

that makes use of image processing and is predicated on its outcomes is weed identification. The automated movement of the robot created by [116] was made possible by the integration of hot pipes along the lanes. Reference [117] developed an autonomous steering system for an avenue poison sprayer by resonating ultrasonic waves towards ultrasonic sensors via a rustproof steel pipe. Reference [118] achieved an efficient design and manufacture of a small disinfection robot for greenhouse jobs. Their robot used a fuzzy approach to find paths. Reference [119] used vehicle navigation and command control to perform harvesting and disinfection in the greenhouse. In the greenhouse, a strong, stiff belt is used for vehicle control. A remotely controllable and viewable disinfection robot was employed by [120]. Reference [38] created a four-degree-of-freedom robot that uses the plant bulk volume to execute spraying. The robot moves through the plant rows, halts when it comes across plant stems, and then gradually opens its manipulator. A road lane painting robot was developed by [121] to identify broken lane markings and apply touch-up paint. By reducing the number of joysticks and making the robot entirely automated rather than only semi-automatic, [122] enhanced the technology of the computer-aided system design for the shortcut robot. It has been shown that self-sensing metakaolin geopolymer sprayed by autonomous spraying robots on a concrete substrate works effectively. A BIM-based robot task planning system was proposed and a prototype was made by [123] to generate a job plan for an inside wall spraying robot. Reference [124] provided a design technique for control parameters that ensured the spraying robot consistently maintained the required precision in the optimal task workspace. Reference [125] developed a spraying robot with a robotic arm with end effectors and a movable platform for interior building applications. An innovative method for reproducing nonuniform, realistic grayscale pictures on large surfaces was developed, utilizing a standard industrial spray-painting robot. Reference [126] described a robotic foam concrete application method that included details on the robotic device and path planning. Reference [42] created a robot that can intelligently spray wall construction materials. To address the discrepancy between the tiny robot size and the vast single operating range, the retractable robot structure was developed.

C. DESIGN CONSIDERATION FOR PRECISION SPRAYING OF AGRICULTURAL ROBOTS

Designing precision spraying systems for agricultural robots, whether aerial or terrestrial, requires numerous critical factors to assure the spraying process's effectiveness, accuracy, and sustainability. These considerations address the distinct issues presented by each platform while attempting to maximise agricultural yield. The following is a full overview

TABLE 4. Robot platforms and its description.

Robot/ Reference	Platform Specifications	Systems modules	Description
Patch sprayer [41]	4-wheel drive	Control systems, Drug supply system, GNSS DOVE-E482, Extender, emergency power supply device, Electric cylinder, Suspension system, Walking chassis, Electromagnetic nozzle	A lightweight and energy-efficient, A system that integrates error adjustment techniques for targeted patch spraying, integration of sensors utilizing GNSS, IMU, precision maps for precise positioning and control, and direct injection spraying with solenoid valves of a precision.
Weed control robot platform [42]	4 wheel drive four-skid steering- 5-degree of freedom arm, 8 mm thick plexiglas panel	5-degree of freedom arm, ActivMedia Pioneer3 AT, Pentium III based embedded computer with a 20 Gb hard drive and an arm with a gripper, two servomotors rotated each joint of the arm, payload of approximately 150 g.	Navigate autonomously within the field, positioning for weed treatment, robot ensures minimal herbicide use while maximizing efficacy.
CROPS Manipulator [46]	4 wheel platform	Six degrees of freedom, precision-spraying end-effector, R-G-NIR multispectral imaging, an optical sensor system, and a precision spraying actuator, an axial fan, an airflow straightener, an airflow cone, a spray nozzle, a pesticide control valve, and connections to the pesticide circuit and to the electronics.	This system allows for early detection and targeted treatment which contrasts with the traditional method of uniform pesticide application, which is less efficient and more harmful to the environment.
High clearance Tractor platform [113]	4 wheel drive	Control systems, Water tank, Collapsible spray bar trusses, Water pipeline 4.Intelligent control systems	High-clearance tractor equipped with a variable sprayer for uniform foliar fertilizer distribution, optimizing machine parameters to improve spraying uniformity, reducing fertilizer use, and minimizing environmental impact.
Yanmar [114]	Crawler type robot platform	Electrostatic spraying technology, air-cooled, four cylinders,	Lightweight and compact design, minimizing soil compression and enabling operation on slopes.
BoniRob [115]	Flexible platform with 4 wheels that can be steered separately,	Vehicle comprises 16 degrees of freedom, implemented by a mix of electro and hydraulic actuation, equipped with a number of dedicated control units: 4 Motor controllers, motor and hydraulic interface, navigation control unit and application control unit, control units are connected by Ethernet and communicate using TCP/IP, multi-sensor fusion approach, integrating various sensors such as spectral imaging and 3D time-of-flight cameras, Real-Time Kinematic Differential GPS (RTK-DGPS) system for precise positioning.	Phenotyping maize and wheat by automatically identifying and mapping individual plants, fertilizer distribution, map plant diseases using spectral imaging data, providing valuable information for precision agriculture.

of key design considerations, including references to relevant scientific studies when possible.

1) AERIAL (DRONES)

- Stability and Control: Aerial spraying drones require advanced flight control systems to stay stable, especially in windy circumstances. Accurate altitude control is required for consistent spray patterns, which stresses the need of stability for drone-based spraying systems.
- Navigation Systems: Precise path following requires high-precision GPS paired with inertial navigation systems. Drones must autonomously navigate complex field geometries, as explored demonstrating the integration of GPS and vision-based systems for autonomous navigation in agricultural environments.
- Nozzle Design: Lightweight, efficient nozzles that can work at different altitudes are essential. It is found that electrostatic nozzles are particularly effective in decreasing drift.
- Variable Rate Spraying: Drones fitted with sensors that modify spray rates in real time provide precision while reducing chemical use. This is reinforced by study which examines variable rate technology in aerial spraying.
- Battery Management: Due to their limited battery capacity, drones must be energy efficient. It found that optimising flight trajectories and lowering component weight can extend operational time.
- Renewable Energy Integration: Incorporating solar panels or other renewable energy sources could be a solution for extending drone operational ranges.
- Cloud-Based Systems: Study on IoT and cloud integration in agriculture discusses how drones can transfer data to cloud-based systems for real-time analysis and decision-making.

2) TERRESTRIAL (GROUND-BASED VEHICLES)

- Terrain Adaptability: Ground robots must be able to navigate a variety of terrains, including hills, muddy

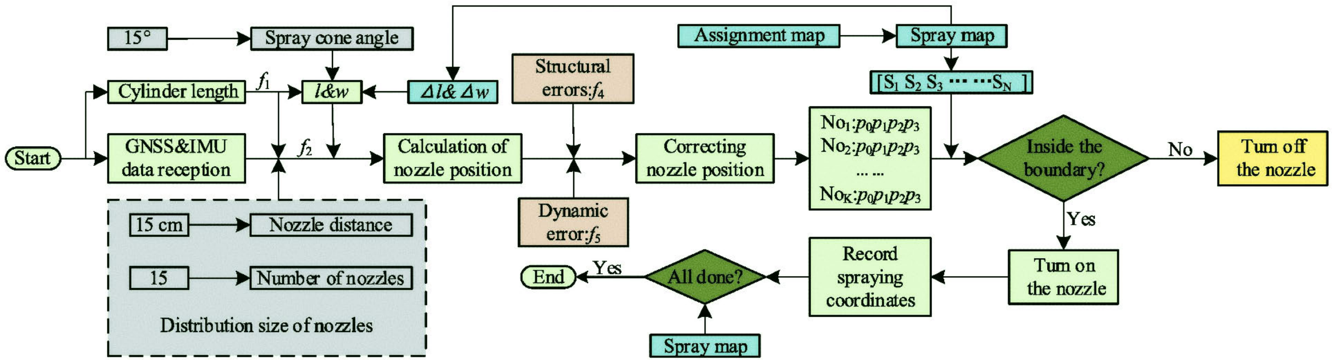

FIGURE 15. Control strategy of the nozzle sprayer [41].

fields, and obstructions. The study on autonomous field robots discusses the importance of robust suspension systems and all-terrain tires for smooth operation.

- Path Planning: Advanced path planning algorithms are essential for optimising coverage and avoiding obstructions. A fundamental rethink is required to provide insights on the development of successful path-planning algorithms for ground-based agricultural robots.
- Precision Nozzles: Ground-based sprayers can use more durable and adjustable nozzles, allowing for targeted application to specific plant sections.
- Controlled Droplet Size: Managing droplet size is critical for preventing drift and providing even coverage. Atmospheric loss of pesticides above an artificial vineyard during air-assisted spraying are conducted in a comprehensive examination of how controlled droplet sizes can be optimised in ground-based spraying systems.
- Hybrid Power Systems: Ground robots frequently use hybrid systems that combine battery and fuel generators. According to the research conducted on the resource conserving mechanization technologies for dryland agriculture, an efficient power management is required to balance the energy demands of propulsion and spraying systems.
- Extended Operation: Ground-based robots can run for longer periods of time, which requires strong power systems that properly regulate energy consumption, as noted by the precise robotic weed spot-spraying for reduced herbicide usage and improved environmental outcomes.
- Onboard Processing: Real-time underwater onboard vision sensing system for robotic gripping experiments found that ground robots often have more powerful onboard processing units for real-time decision-making.

Precision spraying systems for both aerial and terrestrial agricultural robots can be optimised for increased efficiency, accuracy, and sustainability in farming operations by addressing these design factors and referencing relevant publications.

IV. SPRAYING TECHNOLOGY

The efficient use of pesticides can be quite a handful in the control practices of plant pests and diseases to increase crop productivity [127]. The quality and the quantity of the crops are enhanced by using these agrochemicals. However, there has been an increase in environmental risks in recent years [6], adding that a significant amount of the production cost is utilized by the pesticide's application [52]. The over-application of pesticides or inefficient spraying techniques or equipment may cause serious damage to the health of humans and the environment [128]. Applying the pesticide effectively is a critical activity requiring efficient spraying machinery with enhanced and proper calibration and relevant regulations to reduce off-target spray deposition. The design and the application of the spraying technology are some factors that influence the degree of off-target spray deposition.

This section describes the analysis of spraying technology and its applications. There are six types of agricultural sprayers or tools commonly used in the agriculture sector and gardening.

A. COMMONLY USED SPRAYERS

Efficiency and effectiveness are determined by the quality and quantity of the active composite in each droplet that adheres to the targeted area. Commonly used sprayers include [129]:

1) KNAPSACK SPRAYER

It is a gas sprayer initiated by the mechanism tool and moved by hand, forcing the liquid inside the tank to burst out at the end of the tip. The liquid bursts outside, which leads to the air hole every time the pump handle is moved. This will increase the pressure inside and force the pesticide composite out of the valve, then bursting the target area through the nozzle. The gas pressure ignited by the pump is constant at 0.7 – 1.0 kg/cm2 or 10-15 Psi. To utilize this pressure, the user must pump out up to 8 times [130]. The type of knapsack sprayer includes:

1) Knapsack manual sprayer: This type works manually by the hand movement mechanism to obtain a certain gas pressure level. This is made of plastic and comes in a multi-size capacity, starting from 4 to 9 liters [131].
2) Knapsack electric sprayer: This sprayer uses an electric pump mechanism, and the tank capacity is 5 to 8 liters for the bigger size of 16 liters. Farmers are widely choosing the knapsack electric sprayer as it does not work with the hand pumping mechanism. Hence, the farmers can focus more on the weeds and the pesticides for proper precision delivery [132].
3) Knapsack Power Sprayer: This is the farmer's preference for the sprayer and can be easily found in the market. The energy pumped from the high-pressure motor machine can take up to 8 liters per minute. This machine requires fuel and can also be used as a mixture of oil and gasoline in a ratio of 1:25 [133].

2) MOTOR SPRAYER

This uses a machine that generates a pump contraction mechanism and forces the liquid to burst out of the tank as needed. The varieties of these motor sprayers depend on the type and brand of the manufacturer. Commonly used sprayers of this kind are the boom sprayer and the mist blower power sprayer [134].

3) CDA (CONTROLLED DROPLET APPLICATION) SPRAYER

This sprayer is different and is not driven by gas pressure but relies on gravitational energy and disc rotation. The composites in the tank will flow towards the nozzle through the hose and then be received by the jagged disc. When this jagged disc rotates, the liquid will be spread outward toward the target. A battery of 12 V powers the jagged disc, and it activates the rotation of up to 2000 rpm with a droplet size of 250 microns. This droplet size is perfect for delivering on the weeds, which is why the sprayer is named a controlled droplet application (CDA) sprayer [135].

4) TRACTOR SPRAYER

Nowadays, tractors are used not only for plowing land but also for pesticide delivery. The machine and the tank are carried on at the rear side, which protrudes towards the crops used for pesticide spraying [136].

5) HAND SPRAYER

This is the most modest and cheapest and is operated by hand. These are utilized mainly for spraying leaf fertilizer and simply watering the plants [137].

6) DRONE SPRAYER:

In recent advancements, drones have been used for military services and many applications, like plant sprayers. This helps the farmers with a faster and easier spraying process. In many countries, it is still rare to use drone spray. Nonetheless, it is ever-increasing and expected to decrease harvesting failure due to pests and diseases. citespoorthi2017freyr.

B. SPRAYER SELECTION

Some specifications can influence the sprayer selection, which includes nozzle quantity, nozzle pressure PSI range, flow rate capability, pump type, tank volume capacity, spray coverage (swath) potential, vertical and horizontal spray distance, sprayer portability, and system hose length. Selection of the sprayer for the right type of work requires understanding the different sprayer types, their engineering, and performance specifications [138]. The following are the main criteria that have to be put into consideration while assisting with the spray job and sprayer selection:

1) Spray area size: The sprayer's coverage capabilities and the volume capacity are directly connected to the total size of the area needing to be sprayed [139].
2) Spray plot location and terrain: Some spray areas are readily accessible for spray operations, and other sprays require traversing rugged terrain [140].
3) Spray fluid rate refers to the nozzle's output volume (GPM) based on the sprayer's pump's specifications. Spray pumps can be modified for the spraying systems [141].
4) Sprayer fluid pressure: Fluid pressure refers to the nozzle's output pressure (psi). The maximum sprayer psi is based on the sprayer pump, which correlates directly with the vertical and horizontal spray distances. Knowing the specific pump-to-nozzle psi to reach the target areas with spray fluid in many applications [142].
5) Sprayed chemicals: For proper utilization of the chemical spray, knowing which and what kind of spray target is essential, which includes crop-short, late-season, tall, unwanted vegetation, fruit orchards, farm trees, and groves. Different agriculture and spray chemicals may better suit the specific spraying systems [116].
6) Total spray volume: This is essential in knowing and understanding the total spray fluid volume the spray may require to cover the target area with the correct spray material. This is important in selecting the sprayer depending on the tank capacity and other potential application refill frequencies [143].
7) Tank capacity: The sprayer remains operational only when the fluid is present for the spray and when the nozzle quits refilling. A good storage tank should satisfy spray flow rates, application frequency, and total spray area size [30].
8) Spray application frequency: Sprayer selection is influenced by the spraying frequency and the sprayer equipment overall. It depends on the interval of the growing season as well [143].
9) Spray duration: Certain sprayers may be more suitable for a certain time frame if the operation needs to be performed in a specified time frame due to the

crops and other constraints. Knowing the duration of the complete spraying jobs can be useful in regular operation management and better understanding [144].

V. SPRAYING TECHNIQUES

The efficient use of pesticides can be quite a handful in the control practices of plant pests and diseases to increase crop productivity [127]. The use of these agrochemicals enhances the quality and quantity of the crops. However, there has been an increase in environmental risks in recent years [145] adding to the fact that a significant amount of the production cost is utilized by the pesticide's application [146]. Overlying pesticides or inefficient spraying techniques or equipment may cause serious damage to the health of humans and the environment [147]. Applying the pesticide effectively is a critical activity that requires efficient spraying machinery with enhanced and proper calibration, along with relevant regulations to reduce off-target spray deposition. The design and application of the spraying technology are some factors that influence the degree of off-target spray deposition.

Spraying is accommodated in a variety of applications [35], such as:

1) Herbicides for the reduction of weeds in competition with the plant
2) Fungicides, to reduce the effects of fungal infections
3) Insecticides, to reduce or control the insects and pets
4) Micro-nutrients, to supply nutrients like manganese and boron

The main purpose of the sprayer is to divide the liquid into multiple droplets of the appropriate size and uniformly distribute them over the surface that is to be protected [148]. The other function of the sprayer is to avoid excessive application by regulating the amount of insecticide that might be harmful overall or as waste. The large droplets sprayed on the surface to wet the entire area should be used for proper application. Also, the extremely fine droplets, which are less than 100 microns, are diverted by air currents and wasted. The uniform application should be obtained by allowing constant output from the machine and uniform droplet travel.

The significant factors influencing the degree of spray deposition off-target are the design and application of the spraying technology [149]. Spray drift has the potential of not only losing the spray but also putting it at risk to the environment and humans [150]. Spray drift is influenced by many factors, which include spraying technology, spray characteristics, operator skill, and execution [65]. Certain elements contribute to the degree of the drifts, such as micro-climatic factors like wind speed, wind direction, temperature, and relative humidity [151]. The spray technology aims at the effective and economical application of the spray with a precise quantity of the chemical to the set target with a minimum and a reduced threat to environmental pollution. Conventional pesticide application practices need to have developed practices to increase yield, be cost-effective, and have a lesser impact on environmental pollution and human health [152]. The collocated reason for the conventional method is the increase in the application amount because there is no proper application method for spraying nozzles, crop foliage detection, or weather parameters. There is a variation from crop to crop and from plant to plant in terms of canopy and foliage.

The application techniques should be target-oriented for the safety of the non-targets so that a safe environment is ensured. Hence, proper knowledge of the pest problem, proper selection of the application equipment, and skillful pesticide dispersal methods are important. The decision on the time of application will be determined by the most susceptible stage of the pest. The mobility and size of the pest also determine the requirements for coverage and spray droplet size. Reference [33] the mode of the pesticide action, its relative toxicity, and other properties of physiochemistry help in handling the precautionary measures, agitations, and requirements. Also, complete knowledge of the equipment is necessary for developing the desired skill of operation, selecting and estimating the number and type of equipment that is needed to treat the crop for the minimum amount of time, and optimizing the use of the equipment. The success of pest control operations through pesticide application greatly depends on the following factors [153]:

1) Quality of pesticide
2) Timing of application
3) Quality of application and coverage

Even if a good-quality pesticide is used and the optimum timing for the application of the pesticide is also adopted, it will not yield good results unless the pesticide is applied properly. Hence, the quality of the pesticide is also very important in pest control operations. The following points are to be ensured for proper control operations [139]:

1) Proper dosage should be applied evenly
2) The toxicant should reach the target
3) Proper droplet size
4) Proper density of droplet on the target

A. TYPES OF SPRAYING TECHNIQUES

Spraying techniques are classified according to the total volume of the liquid applied per unit of ground area [63]:

1) High volume (HV) sprayer (more than 400 liters/ha),
2) Low volume (LV) sprayer (5 to 400 liters/ha) and
3) Ultra-low volume (ULV) sprayer (less than 5 liters/ha).

The selection technique depends upon the type of vegetation, the kind of pests, and the approach to the field. The high-volume spraying technique was initially used for the pesticide's application, but with the change in the pesticide's application, it is now used with the least amount of carrier or diluent liquid. Depending on the size of the droplets, the spraying application also differs [49]. Fine droplets are utilized and sprayed for the control of pests, insects, or diseases. The larger droplets are used for the herbicides.

As the number of fine droplets produced by the device increases, so will the accumulation in the target area. It is important to consider the size of the droplet, as it affects the penetration distance and the drift toward the target area of the plant [36]. The optimum droplet is given for different targets in the below table:

TABLE 5. Droplet sizes for different targets.

Target group	Droplet size (microns)
Flying insects (drift)	10-15
Crawling and sucking insect (drift)	30-50
Plant surfaces (limited drift)	60-150
Soil application (no drift) such in herbicide application	250-500

In the plant protection equipment, the sprayers can also be sectioned as the below class:

B. ENERGY BASED SPRAYERS

1) BASED ON HYDRAULIC ENERGY

In this subsection, it is divided into two types such as manually operated and powered operated [154]. In manually operated it consists of

1) Syringes, slide pump
2) Stirrup pumps
3) Knapsack or shoulder-slung: lever-operated Sprayer, piston pump type, Diaphragm pump type
4) compression sprayer: hand compression sprayer, conventional type, pressure retaining type
5) Stationary type: foot-operated sprayer, rocker sprayer

In the powered operated [155], it consists of

1) High-pressure sprayer (hand-carried type)
2) High-pressure trolley/Barrow mounted
3) Tractor-mounted/ trailed sprayer
4) High-pressure knapsack sprayer
5) Aircraft, aerial spraying (fixed-wing helicopter)

2) BASED ON GASEOUS ENERGY

In this subsection, it is divided into two types: 1. manually operated and 2. Powered operated. When manually operated, it consists of

1) hand-held type

In the powered operated, it consists of

1) Knapsack, motorized type
2) Hand/ stretcher carried type
3) tractor mounted

3) BASED ON CENTRIFUGAL ENERGY

In this subsection, it consists of

1) Hand held battery operated ULV sprayer
2) Knapsack motorized type
3) Tractor/ vehicle mounted ULV sprayer
4) Aircraft ULV sprayer

4) OTHER SPRAYERS

In this subsection, it consists of

1) Aerosol sprayers
2) Liquefied-gas type dispensers
3) Fogging machines
4) Exhaust nozzle sprayer

With the advancement in technology, spraying has also shifted the pesticides application technology such as:

1) Variate rate sprayers [156]
2) Electrostatic sprayers [157]
3) UAV sprayers [158]

These technologies have changed the pesticide application system with the use of IoT sensors for the detection of weeds and pests, plant canopy and the measurement in foliage, leaf structure calculation, and sensing weather parameters to apply the measured number of pesticides on the targeted area of the plant or the crop. With this advanced sprayer, the effect of the pesticide's exposure on the water, soil, and environmental contamination has reduced with the reduction in the spray drift. The overdose of the pesticide's application is also reduced by the control of the pesticides at the spray nozzles and quick detection of the structure and geometry of the crops and plant's canopy.

C. VARIATE RATE SPRAY

Farmers and academics alike are drawn to the variable spray because to technological advancements. It has demonstrated a significant progress in the use of real-time sensor-based target detection technologies. Among the sensors utilized for the variable sprayers' feature identification of the target region are LiDAR, infrared, and ultrasonic sensors. The control unit of the spray device modifies the spray rate in real-time, enabling precise sprays that are crucial for the canopy. The first factor to be taken into account for improved spray efficiency and precise droplet deposition on tree crops is the measuring of the plant canopy. This is a result of the plant canopies' altered shape, which varies in height and width [136]. Due to its ability to decrease off-target application and boost spray deposition rate for target zones, this technique is most beneficial for orchards and vineyards. Due to its ability to lower pollution during spray application, variable spray technology is expanding quickly [144].

D. ELECTROSTATIC SPRAYERS

The early 1930s saw the creation and development of these electrostatic sprayers. Increasing the spray deposition and penetration of the canopy is the primary essential function of the electrostatic sprayers. With this technique, each drop that emerges from the nozzle has static charge. As a result, the plant, which has a neutral charge, and the droplets begin to attract one another. The high energy charge of the droplets in this system is achieved by injecting air into the spray nozzle, which enables the drops to reach the plant quickly before they become volatile [157]. The repulsion between the drops is caused by the same charge that each drop emits from the spray nozzle. Even in obscure or occluded areas, the plant is consistently and securely exposed to this repulsion between the droplets. These electrostatic sprayers save a significant amount of pesticide needs and have a great spraying efficiency. This spraying technique reduces the dangers to human health, environmental contamination, and drift. Because they employ a 5L/ha pesticide solution and generate small droplets with a diameter of between 50 and 120 microns, electrostatic sprayers are sometimes known as ultra-low volume sprayers [159]. Although this kind of agricultural spraying is not a novel approach, it is being developed in conjunction with environmental concerns and production technology research on electrostatic spraying techniques. Because of this, this method is regarded as the most sophisticated spraying equipment for effectively applying pesticides to crops and orchards. Electrostatic spraying has been shown to have a threefold or more increase in deposits and much promise. Additionally, deposition is increased [51] by adding an electrostatic charge to the spray droplets of the spinning disc nozzles and the hydraulic nozzles. The kinds of electrostatic charging sprays listed below are:

1) Corona charging: The liquid droplets get electrically charged when an ion with a comparable polarity is applied by the pointed electrode at a high voltage. By using this technique, the sprays from the rotary and hydraulic nozzles may be changed.
2) Contact charging: The nozzle or the spray liquid system is directly linked to the high voltage potential [160]. As the spray liquid and spray droplets disintegrate, the charge is transferred via conduction to them. In conductive liquids, this system functions effectively, yet it requires excellent insulation throughout.
3) Induction charging: The spray droplets are charged by the electrical field force. Good insulation between the charging electrodes and the conductive liquid is necessary for this system [161]. The electrostatically charged pesticide sprayer works well with the electrodyne sprayer as well. Applying a high potential of 13 to 24 KV to the spray head with the pesticide bottle and electro-dyne nozzle combo causes the spray to break up into minuscule droplets that range in size from 30 to 50 *micrometers*. Consequently, in addition to the significantly enhanced pesticide deposition, the treatment volume is considerably decreased to 0.5 to 1.0 L/ha. The introduction of good dispositioning qualities has resulted in very little pesticide drift and waste [162]. Better pesticide deposit, little drift losses or waste, low power consumption, a restricted range of droplet sizes, labor and time savings, minimum volume per acre, etc. are some benefits of electro dyne spraying. The electro dyne sprayer has a few drawbacks, including as severely depositing top leaves, working best with broad leaf crops, requiring specific electro dyne formulations, and not having access to electro dyne formulations for all pesticides.

E. UAV SPRAYERS

Unmanned aerial vehicle aircraft (UAV) sprayers are used to prevent human health issues [163]. Unmanned Aerial Vehicles (UAVs) find extensive application in precise technology where personnel and equipment provide challenges to operation. Both military and civilian activities employ a range of UAV types [164]. Additionally, the ability to use UAVs to decrease spray loss from spray drift through precise spray delivery, flawless target identification by the sensor, and appropriate handling has risen thanks to advancements in vision and sensor systems. Crop productivity has grown along with pesticide efficacy against weeds and insects in the field because to advancements in spray application technology. These cutting-edge pesticide application technologies handle issues with target identification, spray drift, weather impacts, control flow nozzles, and spray loss [165]. Fine droplet spray nozzles and ultra-low volume sprayers both lessen the issue of laborious tank refills. Additionally, technology ranging from pest and weed identification to spray application nozzles has affected crop upkeep [136].

F. SPRAY NOZZLE CLASSIFICATION

A spraying nozzle breaks the spray liquid into tiny droplets and emits the liquid in a very thin shape. Consequently, the droplets are thrown out of the nozzle opening. As a result, several designs are applied to provide a suitable droplet size spectrum. In order to split the liquid into droplets, energy is required. These spray nozzles fall into more categories, such as:

1) Hydraulic energy nozzles
2) Gaseous energy nozzles
3) Centrifugal energy nozzles
4) Thermal energy nozzles

For the high-volume spraying techniques, hydraulic nozzles are included into every sprayer. Low-volume sprayers typically use the backpack style with either a gaseous energy nozzle or an air blast nozzle. The hand-held, battery-operated sprayers, also known as CDAs [166], have a rotating disc-style nozzle that uses centrifugal force. For ULV applications, fogging machines are utilized in conjunction with thermal energy nozzles, which are also referred to as hot tube nozzles [167]. In recent times, charged spray droplets for ULV applications have also been created using electrical energy [168].

1) HYDRAULIC ENERGY NOZZLES

The most popular kind of hydraulic energy nozzle for applying pesticides is this one. Pesticides are sprayed using the following kinds of hydraulic nozzles [169]:

1) Hollow cone type: This kind of hydraulic nozzle is highly common for applying fungicides and insecticides. It creates a spray pattern that resembles a hollow cone and consists of a variety of droplet sizes. The nozzle in this design is the simplest; it is composed of brass metal with a drilled hole in the center, and

it spins with tangentially cut grooves to create the motion necessary for the spray liquid to separate into droplets as it emerges from the nozzle under pressure. A different design has a stainless-steel disk with a spray that emerges from a swirl chamber behind it via a central circular hole. The nozzle body, which has threads for screwing or connecting it to the lance or boom, is appropriately equipped with the swirl plate and disk. The hollow cone nozzle's typical operating pressure is 40 psi. Because the spray particles travel in limitless angles and different planes, allowing for higher spray penetration, these cones are the ideal for treating complicated objects [170]. Nevertheless, because of the potential for line spray particle drift and the challenge of achieving a uniform spray distribution throughout the swath, these sprays are not advised for use in herbicide treatments. It is possible to alter the liquid pressure fluctuation by adjusting the spray angle, droplet size, and discharge rate. Because of abrasive action and chemical corrosion, they are quickly worn off. The plastic or stainless steel tips aid with uniform spraying and are more resistant to wear.

2) Fan nozzles: Also known as flat fan nozzles, their typical operating pressure is around 40 psi. A flat spray sheet is produced when the elliptical spray liquid is flung out of the aperture. Band spraying is another application for these. In order to provide uniform dispersion, the nozzle is often employed with the booms spaced appropriately apart from one another. Herbicide applications with these nozzles are possible, but they must be carried out at low pressures (around 15-20 psi) to prevent fine droplet drift [53].
3) Impact nozzles: They are often referred to as deflector nozzles or flood jet nozzles. This hole's spray is redirected at an angle when it hits a smooth, sloping face. As a result, the spray is applied in a wide-angled fan pattern as a sheet. These nozzles are used to apply herbicides in a coarse droplet spray pattern. These are carried out at 15–25 psi of low pressure [171].
4) Adjustable nozzles: These are typically utilized with high-pressure hydraulic sprayers for spraying trees, foot-operated sprayers, and rocking sprayers. Another name for them is triple-action nozzles. This is due to the fact that different spray patterns may be produced by adjusting the spray liquid's swirl velocity within the eddy chamber. Simple changes can be made to achieve a jet spray, a medium coarse spray pattern, or a spray pattern of small spray particles [172].

2) GASEOUS ENERGY NOZZLES

A stream of air traveling at a high speed is injected with the liquid in the gaseous energy nozzle. The liquid forms ligaments because of the push of the air, and eventually breaks into tiny spray droplets. The liquid flow is then monitored after the airstream carries these droplets to the target. The nozzle design determines the size of the spray droplet. In this kind of air blast nozzle, a motorized backpack or mist blower is installed to enhance the size of the droplet by raising the liquid flow rate. In this instance, the bigger size of the sprayer's hydraulic nozzle atomizes the liquid first, and the air bursts subsequently distribute the droplets even further. According to González [13], this type of nozzle is also utilized for gaseous energy in ULV spraying.

3) CENTRIFUGAL ENERGY NOZZLES

On a fast-rotating disc, the liquid is fed and is carried by centrifugal force to the outermost edge of the disc for issuing the spray droplets. Also, if the liquid is fed again to the rotating cylinder cage of the line mesh, it also produces a fine spray. Depending upon the speed of the revolving disc and the cage, the size of the droplets also varies accordingly. For a droplet to have a narrow spectrum, the disc has to be a serrated tooth on the periphery. Besides the speed of rotation, the physical properties of the spray liquid are also important for usage in ULV and LV spraying methods [173].

4) THERMAL ENERGY NOZZLES

Also called as hot tube nozzles, the fogging machines work with the thermal energy nozzle. In the stream of hot gases at the exhaust of the engine, the spray liquid is injected which then vaporizes because of the high temperature. This then condenses when ejected out of the nozzle due to the temperature outside the nozzle. This forms a fine fog. This thermal exhaust nozzle sprayer, which is mounted on the vehicle is used for ULV applications and in the control of the locust in the fields. This pesticide-fogging pulse jet engine model is also used for public health purposes [174].

VI. SENSOR-BASED SPRAYING

Precision agriculture, driven by the need for efficient resource management and sustainable farming practices, has revolutionized the agricultural industry. One crucial aspect of precision agriculture is the precise delivery of agricultural chemicals, such as fertilizers and pesticides, to optimize crop yield and minimize environmental impact. Traditional blanket spraying methods often result in over-application, leading to unnecessary chemical use, increased costs, and potential ecological harm [176], [177], [178].

To overcome these challenges, the evolution of sensor-based spraying systems has emerged as a groundbreaking solution. Sensor-based spraying systems integrate advanced sensor technologies with intelligent algorithms, enabling precise and targeted application of agricultural chemicals. By providing real-time data on crop health, weed presence, and environmental conditions, these systems offer unprecedented accuracy and efficiency in chemical delivery, significantly improving the overall effectiveness of agricultural practices. The evolution of sensor-based spraying systems can be traced back to the advancements in sensor technologies and their integration into agricultural machinery. Imaging sensors, such as cameras and hyperspectral imagers, have

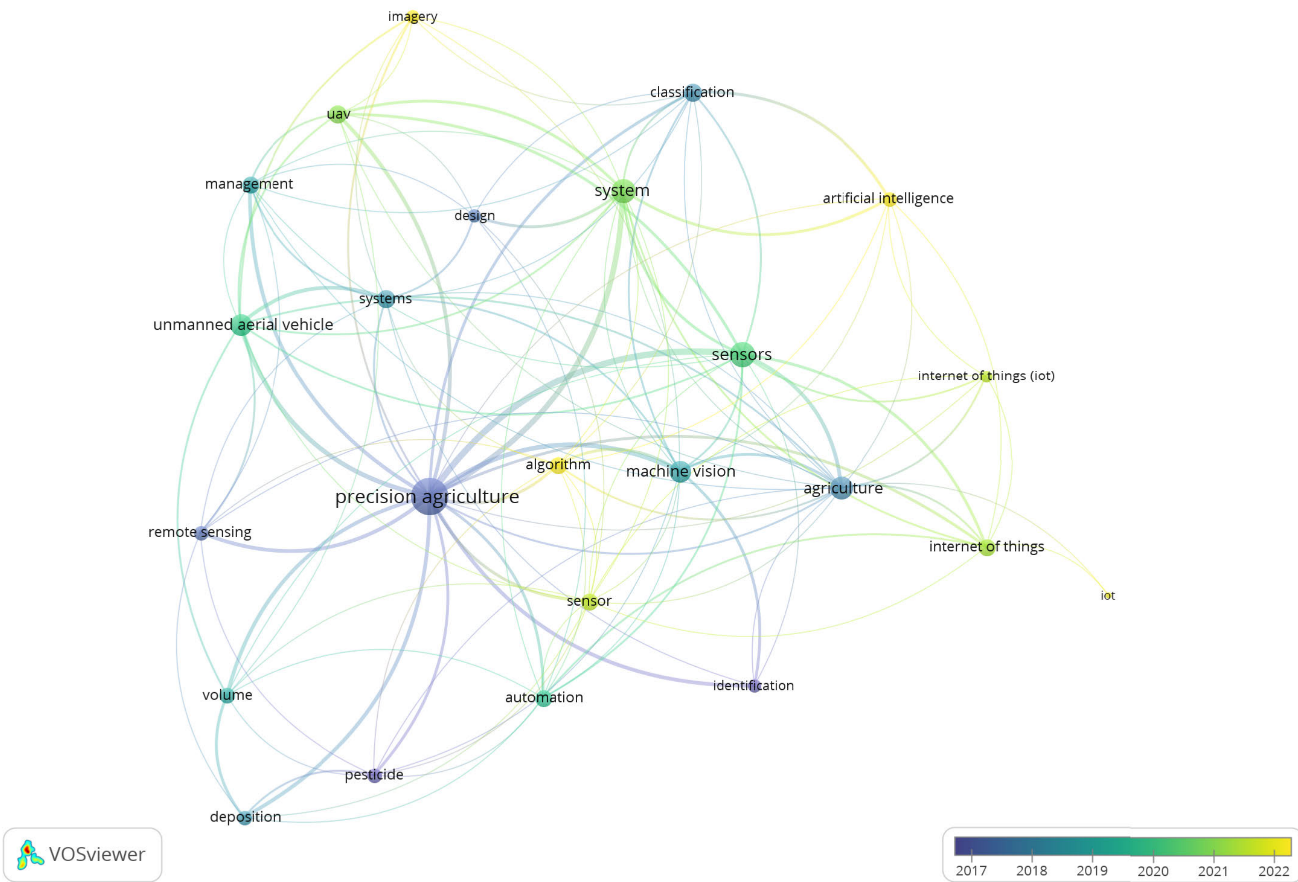

FIGURE 16. Sensor-based spraying keywords used in precision agriculture-related from 2014 until 2024.

enabled the detection and discrimination of specific targets, allowing for precise targeting of chemical applications. Laser-based sensors, including LIDAR (Light Detection and Ranging), have further enhanced the capabilities by providing accurate measurements of crop canopy structure and density. Additionally, spectrophotometers and multispectral sensors have allowed for the analysis of reflectance properties, facilitating vegetation mapping and weed control strategies [176], [179].

The integration of sensor data with intelligent algorithms has been a pivotal development in the field of sensor-based spraying. Real-time decision-making and adaptive spraying strategies can now be implemented, taking into account factors such as crop variability, environmental conditions, and weed presence. Machine learning and artificial intelligence techniques enable the creation of predictive models, allowing farmers to optimize chemical delivery based on historical and real-time data [180].

While sensor-based spraying systems hold great promise, several challenges and limitations must be addressed for their widespread adoption. Cost considerations, including the initial investment and maintenance expenses, pose a barrier for small-scale farmers. Ensuring the reliability and accuracy of sensor data is also crucial, as any inconsistencies or errors may lead to suboptimal chemical application. Additionally, effective data management and analysis are vital to extract valuable insights and facilitate decision-making processes. Looking ahead, the future of sensor-based spraying in precision agriculture is promising. Standardization and interoperability across different sensor systems and agricultural equipment are necessary to ensure seamless integration and compatibility. Advancements in sensor technology, including improved resolution, increased spectral range, and reduced costs, will further enhance the capabilities of sensor-based spraying systems. Furthermore, enhanced data analytics and modeling techniques will enable more accurate predictions and customized spraying strategies, leading to higher efficiency and reduced chemical usage [180], [181].

A. SENSOR TECHNOLOGIES FOR PRECISION SPRAYING

Precision spraying in agriculture has been altered by the development of sensor technology, opening up new opportunities for enhancing chemical delivery. The main sensor technologies used in precision spraying are highlighted in this

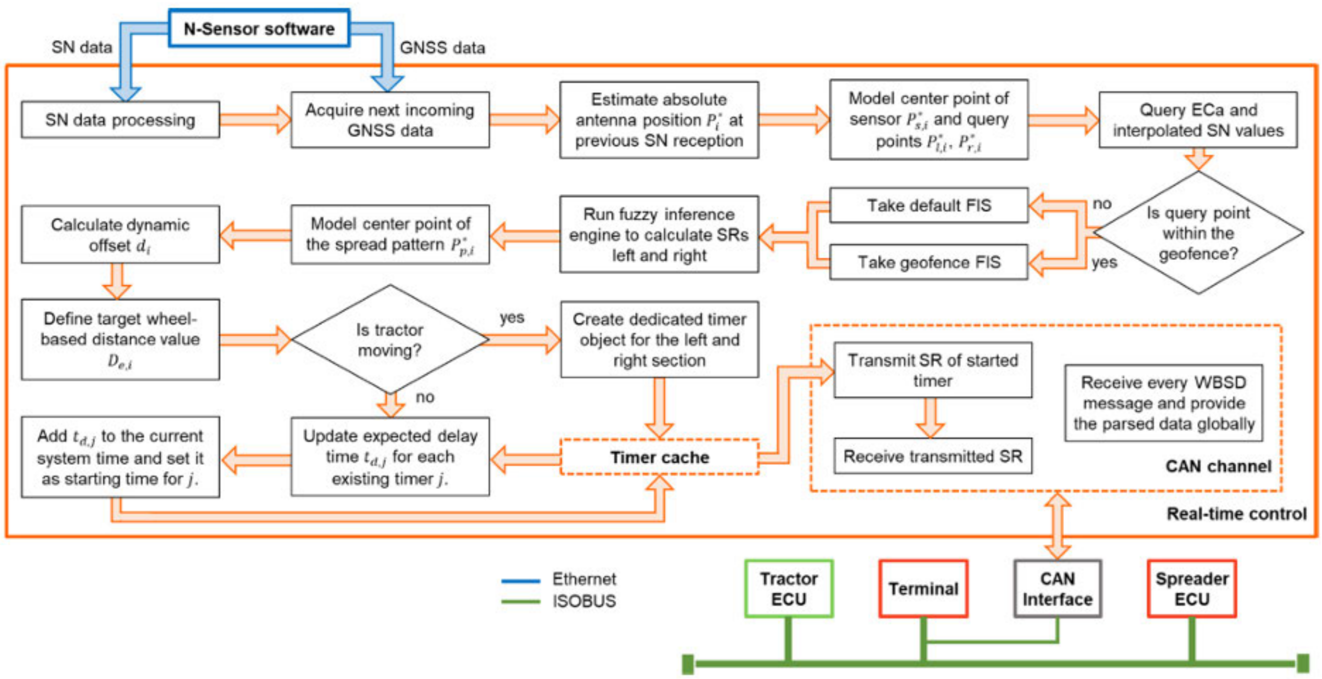

FIGURE 17. Schematic diagram for the real time sensor working principle [175].

overview, including imaging sensors, laser-based sensors, spectrophotometers, multispectral sensors, and the fusion of sensor data [182].

High-resolution photographs of the crop canopy are produced by imaging sensors, such as cameras and hyperspectral imagers, allowing for the accurate detection and differentiation of certain targets. These sensors provide important information on the health of the crop, the presence of weeds, and the detection of diseases, enabling targeted spraying and minimizing chemical waste. LIDAR in particular, a type of laser-based sensor, is essential for describing the crop canopy. LIDAR sensors accurately capture information on crop height, structure, and density by measuring the amount of time it takes for laser pulses to reflect off of things. Using this information, chemicals may be delivered precisely, assuring maximum effectiveness and coverage with the least amount of waste [182], [183], [184].

The reflectance characteristics of crops at various wavelengths are measured using spectrophotometers and multispectral sensors, enabling the investigation of vegetation indices and stress levels. These sensors can recognize crop health indicators and nutritional deficits by analyzing spectral signatures, enabling targeted chemical applications [185].

Precision spraying is further improved through the merging of data from many sensors. A thorough picture of field conditions can be attained by merging data from imaging sensors, laser-based sensors, spectrophotometers, and more. Utilizing intelligent algorithms to process this combined data enables real-time decision-making and adaptive spraying techniques, maximizing chemical distribution by particular field needs [186].

In general, the development of sensor technologies has changed agricultural precision spraying. For target detection, vegetation mapping, and environmental monitoring, imaging sensors, laser-based sensors, spectrophotometers, multispectral sensors, and the integration of sensor data through fusion algorithms offer useful insights. These technologies make it possible to deliver chemicals precisely and strategically, minimizing waste and fostering organic farming methods. To fully utilize the promise of these sensor technologies in precision spraying, future research and development efforts should concentrate on increasing sensor accuracy, lowering costs, and strengthening data analytics [181], [187].

B. APPLICATIONS OF SENSOR-BASED SPRAYING

Sensor-based spraying has opened up a multitude of applications in the precise delivery of agricultural chemicals. This review explores the key applications of sensor-based spraying, including target detection and discrimination, vegetation mapping and weed control, and environmental monitoring and crop health assessment [188], [189].

Target detection and discrimination are crucial in precision spraying to ensure accurate chemical application. Sensor technologies, such as imaging sensors, enable the identification and differentiation of specific targets within the field. These sensors provide real-time data on crop health, weed presence, and disease detection, allowing farmers to precisely target areas requiring chemical treatment. By focusing spraying efforts on specific targets, sensor-based systems minimize chemical waste and reduce the potential for ecological harm [190], [191].

Vegetation mapping and weed control are essential aspects of precision agriculture. Sensor technologies, such as imaging sensors and spectrophotometers, facilitate the creation of vegetation maps by analyzing crop reflectance properties and identifying areas of varying health or weed infestation. This information enables farmers to tailor chemical applications, concentrating on areas with specific needs and optimizing resource allocation. By accurately targeting weeds, sensor-based systems reduce the reliance on broad-spectrum herbicides, promoting more sustainable and efficient weed control practices [204], [205], [206].

Environmental monitoring and crop health assessment play a vital role in precision spraying. Sensor technologies provide valuable insights into environmental conditions and crop health indicators. By integrating data from various sensors, including imaging sensors and spectrophotometers, farmers can monitor factors such as temperature, humidity, nutrient levels, and pest presence. This data allows for informed decision-making regarding chemical application and enables early detection of potential crop stress or disease. By proactively addressing these issues, farmers can optimize crop health and minimize yield losses [207], [208], [209].

The applications of sensor-based spraying in precision agriculture have demonstrated significant benefits. Target detection and discrimination ensure precise chemical delivery, minimizing waste and environmental impact. Vegetation mapping and weed control enable tailored chemical applications, reducing herbicide use and promoting sustainable practices. Environmental monitoring and crop health assessment contribute to optimized crop management, improving overall productivity and resource efficiency [153], [196], [210].

Further research and development efforts should focus on enhancing sensor technologies, data analysis algorithms, and integration capabilities. By improving sensor accuracy, reliability, and affordability, as well as advancing data analytics for real-time decision-making, the full potential of sensor-based spraying in precision agriculture can be realized.

C. INTEGRATION OF SENSOR DATA AND INTELLIGENT ALGORITHMS

Precision agriculture has undergone a revolution with the incorporation of sensor data and clever algorithms, improving the effectiveness and efficiency of chemical administration. The main elements of the integration of sensor data and intelligent algorithms are examined in this review, including cost concerns, the accuracy and dependability of sensor data, and data administration and analysis. Reference [211]. The schematic diagram of the working principle for the real-time sensor used in the spraying technology is shown in Figure 17.

The general adoption of sensor-based systems is heavily influenced by cost factors. For farmers, especially those operating on a smaller scale, the initial investment in sensors and related equipment as well as continuous maintenance costs can be a substantial obstacle. Efforts should be made to create affordable sensor systems and offer assistance to farmers in terms of cost and return on investment in order to promote wider implementation. The creation of commercially viable sensor-based systems can be facilitated by cooperation between technological service providers and agricultural stakeholders [212].

For well-informed decision-making, sensor data must be accurate and reliable. For sensor technologies to work consistently, they must deliver exact data. To confirm the precision of sensor measurements, calibration, and quality control procedures should be put in place. Sensor technology also needs to be strong enough to endure the harsh environmental conditions that are present in agricultural settings. To maximize the use of chemicals and achieve desired results, sensor data must be reliable and accurate [213], [214].

The administration and analysis of data are essential for utilizing sensor data to its maximum potential. Sensor-based systems produce large amounts of data, necessitating effective mechanisms for data storage, retrieval, and processing. The sensor data can be analyzed using advanced data analytics techniques, including machine learning and artificial intelligence, to derive useful insights and enable real-time decision-making. To maximize the usefulness of sensor data in precision agriculture, however, issues relating to data integration, standards, and privacy need to be addressed [215].

Researchers, industry stakeholders, and policymakers must collaborate in order to fully reap the rewards of combining sensor data and cognitive algorithms. To improve interoperability and comparability among various sensor systems, standardized protocols for data collection, exchange, and analysis should be defined. To enable more advanced decision-making capabilities, developments in data analytics techniques, such as machine learning and artificial intelligence, should be pursued [216].

The scope of advances in precision spraying using deep learning is broad, with the potential to greatly enhance agricultural operations by making them more efficient, sustainable, and cost effective. Deep learning approaches provide a variety of options for improving the precision, accuracy, and efficacy of spraying operations, resulting in better crop management and environmental responsibility. Deep learning models, particularly convolutional neural networks (CNNs), can be trained on big datasets to differentiate between plant species, such as crops and weeds. This allows robotic sprayers to precisely target weeds without harming crops, decreasing the need for broad-spectrum herbicides and chemical use. Sprayers can use deep learning to recognise specific sections of a plant that need to be treated, such as diseased leaves or pest-infested areas. This selective technique limits chemical application to only the regions that require it, thereby reducing waste and environmental impact. The use of deep learning models, namely convolutional neural networks (CNNs), to identify plants in real situations

TABLE 6. The past work on real-time sensors for targeted spraying technology.

Sensor	Other components	Objectives of the work	Citation
Ultrasound Sensors	Microcontrollers: Cypress PSOC CY8C29466, LPC1343 Microcontroller, Electro-Magnetic Valves, Custom Monitoring System	To assess the prototype automated sprayer using ultrasonic sensing for the identification of the structures and density of the tree canopies in real-time and to optimize the pesticides spraying at targeted areas.	[210]
LIDAR	Electromagnetic Valves, Pulse Width Modulation (PWM) Signals, Microcontroller and Variable-Rate Control Program	Measures the canopy volume with variable rate algorithm principle based on the spatial dimensions of the canopy to improve the performance of the orchard sprayers.	[211]
Ultrasonic Sensors	Digital Cameras, GPS, Flow Controller, Solenoid Valves, Variable Rate Controller, Custom Software	Accurate application of the pesticides tailored for a particular site and for real-time weed detection to enable a strong relationship between spray coverage and weed height.	[212]
Ultrasonic Sensors, LIDAR	Machine Vision Systems, GPS, Electromagnetic Valves, and Real-Time Processing Unit	With proper precise weed maps, spraying can be regulated with less herbicides having less impact on the environment and improve weed control in row crops.	[213]
Infrared Sensors, Ultrasonic Sensors, Opto-electronic Sensors	Electromagnetic Valves, Real-Time Processing Unit	With controlled administration of the insecticides, fungicides and herbicides, the crops had reduced foliage in the post-emergence stages with no negative impact on the crop output and cost savings.	[214]
LiDAR	RGB Cameras, GPS, Flow Meters, Artificial Intelligence, Electronic Valves, Embedded Computer NVIDIA Jetson Xavier NX	Estimate the canopy density, discriminate between non-tree and trees, adjust the spraying nozzles accordingly for a low-cost smart sensing system with regulated crop sprayers.	[215]
Infrared Sensors, Ultrasonic Sensors	GPS, Electromagnetic Valves, Flow Meters, Control Unit	To accurately and effectively deliver bait treatments by a sensor-controlled spray system for more accurate administration of pesticides, improving crop canopy pest management overall.	[216]
Ultrasonic Sensors	Digital Cameras, GPS, Flow Controller, Solenoid Valves, Variable Rate Controller, Custom Software	Data-driven spraying techniques to reduce the chemical usage by accurately targeting the weeds in the blueberry fields.	[212]
LIDAR, Ultrasonic Sensors	GPS, Electromagnetic Valves, Pulse Width Modulation, Microcontroller and Variable-Rate Control Program, Flow Meters	Creating and assessing a sprayer system that measures the volume and structure of tree canopies in real time using LIDAR technology by precisely targeting specific tree regions for the canopy.	[217]
Infrared Sensors	Deep Learning Algorithms, Spatio-Temporal Filtering, L1 Norm Regularization, Principal Component Decomposition Model, Microcontrollers and Processing Units	Ability to increase the target detection rates while reducing the false alarm under diverse environmental circumstances including poor sight areas.	[218]
Ultrasonic Sensors	Pulse Width Modulation, Solenoid Valves, Microcontroller, Spray Delivery System, High-Speed Camera, Flow Rate Controlled Unit, Embedded Computer with Touch Screen	Investigating the variable-rate sprayer application on the canopy to guarantee the uniform spray coverage and deposition on a range of tree size and species.	[219]
LIDAR	3D Dynamic Measurement System, Terrestrial Laser Scanners, Computational Software	Investigates the link between tree row LIDAR-volume (TRLV) and leaf area density (LAD) by scanning these trees with a 2D Terrestrial Laser Scanner (2D TLS) and creating 3D point clouds.	[220]
Ultrasonic Sensors, Infrared Sensors, LIDAR	Plant Cover Sensors (CROP-Meter), Decision Support Systems (DSS), Pulse Width Modulation (PWM) Solenoid Valves, Embedded Computer Systems	To optimize the application of the sophisticated fungicide spraying system and also measure the crop's biomass density, canopy size and overall health as well.	[221]

are also discussed in the literature. It focusses on how these models might be applied to precision agriculture, specifically recognising crops and weeds for targeted spraying. The work highlights the potential for deep learning to increase the accuracy and efficiency of precision spraying by ensuring that only the intended plants are treated. proposes an innovative strategy for classifying tomato ripeness levels using a hybrid deep learning model. The researchers merged Convolutional Neural Networks (CNNs) and Transformer architectures to take advantage of their respective strengths. This hybrid model, known as a Convolutional Transformer, is very successful at capturing both local properties (best handled by CNNs) and global dependencies (managed by Transformers) of tomato categorisation images.

The findings in some of the papers, apply to precision spraying since proper identification of plant species is critical

TABLE 7. Some sensor concepts and their pros and cons.

Sensor	Basic concepts	Pros	Cons	Applications
LIDAR	Determines the object's distance using the leaser beams' flight time.	High accuracy Faster working Day and night light conditions Can penerate and surpass vegetation	Influence by the weather Poor performance in detection Increased cost Complexity in data processing Issues in adverse weather conditions	Topographic Mapping Urban Planning Autonomous Vehicles Agriculture Forestry
Ultrasonic	Determine an object's distance by computing the sound wave's sensing and receiving times.	Microcontroller easy interface Ease of use low cost Robustness Effective for the solid and liquid target	Susceptible to noise Limited range of detection Dependence of surface properties Material restrictions	Object detection Level measurement Medical Imaging Agriculture Industrial Automation Distance Monitoring
Infrared	That tracks and measures the infrared radiation that things emit.	Low cost Low power consumption Can measure object without contact delivery Reliable in low light conditions Lesser impact on temperature and humidity	Dependent on light intensityfor detecting limited range cannot detect the entire canopy information Spatial resolution deficiency in agriculture.	Temperature measurement motion detection Proximity sensors tod etect the object.
Sensor fusion	Combining data from several sensors to create information that is more complete, accurate, and dependable than what could be found from using only one sensor.	More precise information than a single sensor Lesser errors Improved accuracy Enhances system performances compensating individual sensor at various conditions	Higher cost Increased computational requirements sophisticated combinations requires precise alignment ensure accurate data fusion	Autonomous vehicle to navigate and avoid obstacles Robotics to enhance robot perception and environment interaction Wearable devices to provide comprehensive health Environmental monitoring to analyze the parameters like temperature, humidity and pollution levels.
Machine Vision System	Makes the visible world interpretable and understandable to computers	Provides high accuracy for the 3D plant inspection High preciison in repeatibility task reduces the need for the manual inspection increases the productivity of the machine	Data overload by the high image and video resolution Complexity in desigining, installing and maintenaining High initial costs Limited flexibility in changing the tasks.	Automated sorting in the agriculture and logistics Guiding the robotic systems for navigation and other feedbacks Surveillance and monitors the acitivities of the security systems

for ensuring that pesticides are sprayed accurately. The study emphasises the significance of multi-image observations in improving classification accuracy, which is necessary for precision targeting during spraying operations. Although this study is primarily concerned with disease and pest detection, the deep learning approaches mentioned here are directly applicable to plant recognition in the context of precision spraying. The review discusses several CNN architectures and their usefulness in identifying certain plant situations that may benefit from targeted spraying, hence optimising pesticide and herbicide administration. One paper discusses the creation of a novel robotic sprayer system intended exclusively for precision agriculture. The technology uses deep learning algorithms to recognise tobacco plants in real time, allowing for focused and efficient pesticide and nutrition spraying. The robotic system includes precision spraying technology that changes chemical application based on the exact location and size of the recognised tobacco plants. This tailored method saves chemical waste, decreases expenses, and has a minimal environmental impact. The creation of an autonomous robotic vehicle aimed at improving precision in agricultural seeding processes are present in the literature. The major goal is to develop a prototype capable of autonomously navigating agricultural fields and precisely planting seeds, hence boosting seeding efficiency and accuracy. The potential for breakthroughs in precision spraying using deep learning is vast and transformational. Deep learning has the potential to improve the accuracy, efficiency, and sustainability of spraying operations, thereby playing an important part in agriculture's future. As these technologies advance, they will help to enhance crop yields, reduce environmental impact, and improve farm profitability, opening the way for more sustainable and resilient agricultural systems around the world.

In conclusion, precision agriculture has a lot to gain from the integration of sensor data and cognitive algorithms. However, addressing budgetary issues, guaranteeing the integrity and dependability of sensor data, and putting in place efficient data administration and analysis procedures are crucial for a successful implementation. Sensor-based systems can optimize chemical delivery, increase resource efficiency, and support sustainable farming practices by addressing these difficulties. The integration of sensor data and sophisticated algorithms will be improved through ongoing research and collaboration, opening up new opportunities for precision agriculture.

D. CHALLENGES AND LIMITATIONS

The integration of sensor data and intelligent algorithms has revolutionized precision agriculture, enhancing the effectiveness and efficiency of chemical delivery. This review examines the key aspects related to the integration of sensor data and intelligent algorithms, including cost considerations, reliability and accuracy of sensor data, and data management and analysis [217].

Cost considerations play a crucial role in the widespread adoption of sensor-based systems. The initial investment in sensors and associated equipment, as well as ongoing maintenance costs, can be a significant barrier for farmers, particularly smaller-scale operations. To encourage broader implementation, efforts should be made to develop cost-effective sensor solutions and provide support for farmers in terms of affordability and return on investment. Collaboration between technology providers and agricultural stakeholders can facilitate the development of economically viable sensor-based systems [218].

The reliability and accuracy of sensor data are critical for informed decision-making. Sensor technologies must provide consistent and precise data to ensure reliable performance. Calibration and quality control protocols should be implemented to verify the accuracy of sensor measurements. Additionally, sensor technologies should be robust enough to withstand challenging environmental conditions encountered in agricultural settings. Ensuring the reliability and accuracy of sensor data is vital for optimizing chemical applications and achieving desired outcomes. Data management and analysis are pivotal for leveraging the full potential of sensor data. Large volumes of data are generated by sensor-based systems, requiring efficient storage, retrieval, and processing mechanisms. Advanced data analytics techniques, such as machine learning and artificial intelligence, can analyze sensor data to extract meaningful insights and support real-time decision-making. However, challenges related to data integration, standardization, and privacy should be addressed to maximize the value of sensor data in precision agriculture [219].

To fully exploit the benefits of integrating sensor data and intelligent algorithms, collaborative efforts among researchers, industry stakeholders, and policymakers are necessary. Standardized protocols for data collection, sharing, and analysis should be established to facilitate interoperability and comparability across different sensor systems. Additionally, advancements in data analytics algorithms, including machine learning and artificial intelligence, should be pursued to enable more sophisticated decision-making capabilities [220].

Achieving breakthrough research in precision spraying utilising robots' technology entails tackling numerous critical difficulties with new solutions. Some of the possible solutions that could greatly progress includes:

- **Multi-Sensor Fusion:** By combining data from many sensors (e.g., RGB cameras, multispectral, hyperspectral, Lidar, and ultrasonic), the robot can gain a more accurate and comprehensive awareness of its surroundings, improving its capacity to distinguish between crops, weeds, and other items.
- **High-Resolution Imaging with AI:** Developing higher-resolution imaging systems, along with powerful AI models for real-time plant health assessment, disease diagnosis, and weed identification, can enhance spraying precision.
- **Targeted Micro-Spraying:** Creating methods that allow micro-spraying (for example, targeting individual leaves or portions of a plant) could significantly reduce the number of pesticides needed by focussing just on damaged areas.
- **Advanced Path Planning and Obstacle Avoidance:** Creating more sophisticated path-planning algorithms capable of navigating complicated and dynamic agricultural landscapes, such as avoiding barriers and altering routes in real time to reflect changing field conditions.
- **Modular Robotic Platforms:** Developing modular robotic systems that can be scaled up or down according on farm size and needs. These systems could be built with replaceable parts, allowing for simple updates and customisation.
- **Low-Cost Robotics:** Investigating and developing low-cost robotic systems suitable for small and medium-size farms. This could include using open-source hardware and software, as well as capitalising on economies of scale.
- **Data-Driven Decision Support Systems:** Creating AI-powered decision support systems that can analyse data from a variety of sources (such as soil sensors, meteorological data, and crop models) in order to optimise spraying schedules and strategies.
- **Continuous Monitoring Systems:** Using continuous monitoring systems to provide real-time input on spraying efficacy, enabling for quick modifications and assuring optimal coverage.
- **Automated Data Logging and Analysis:** Using robotic systems to automatically log data during spraying operations, which can then be analysed to improve future spraying techniques and help with long-term field management plans.
- **Human-Robot Interaction and Usability:** Creating intuitive user interfaces that enable farmers to effortlessly control and monitor robotic sprayers. These could be smartphone apps or wearable gadgets that offer real-time updates and control options.

- **Extensive Field Trials:** Conducting field trials across various crops, climates, and terrains to test the effectiveness, dependability, and efficiency of robotic spraying systems in real-world situations.

By focussing on these potential answers, precision spraying research employing robotics technology can result in major improvements in agricultural efficiency, sustainability, and productivity.

In conclusion, the integration of sensor data and intelligent algorithms has immense potential in precision agriculture. However, addressing cost considerations, ensuring the reliability and accuracy of sensor data, and implementing effective data management and analysis practices are essential for successful implementation. By overcoming these challenges, sensor-based systems can optimize chemical delivery, improve resource efficiency, and promote sustainable agricultural practices. Continued research and collaboration will further enhance the integration of sensor data and intelligent algorithms, unlocking new possibilities for precision agriculture.

E. FUTURE DIRECTIONS AND OPPORTUNITIES

The future of sensor-based spraying in precision agriculture holds exciting prospects for advancements and widespread implementation. This review explores key areas of future development, including standardization and interoperability, advancements in sensor technology, enhanced data analytics and modeling, and the importance of adoption and education [221].

Standardization and interoperability are critical for the seamless integration of sensor-based systems. Establishing common protocols and standards for data collection, sharing, and communication will promote compatibility among different sensor technologies and agricultural equipment. This interoperability will enable farmers to leverage multiple sensors and data sources, creating a more comprehensive understanding of field conditions and optimizing chemical delivery. Collaborative efforts among stakeholders, including researchers, industry leaders, and policymakers, are essential to drive standardization initiatives forward [222].

Advancements in sensor technology will play a pivotal role in the future of precision spraying. Continued research and development efforts should focus on improving sensor accuracy, resolution, durability, and affordability. Advancements in imaging sensors, laser-based sensors, spectrophotometers, and other sensor technologies will enable more precise detection, characterization, and mapping of crops, pests, and environmental conditions. Additionally, emerging sensor technologies, such as nanosensors or biosensors, may offer new opportunities for enhanced precision and monitoring capabilities [223].

Enhanced data analytics and modeling are crucial for maximizing the potential of sensor data. The application of advanced data analytics techniques, such as machine learning, artificial intelligence, and data fusion algorithms, will enable more sophisticated analysis of sensor data. These techniques can provide real-time insights, predictive modeling, and decision support systems, optimizing chemical application strategies and resource allocation. Further research and development are needed to enhance the accuracy, interpretability, and scalability of these data analytics methods for precision agriculture [224].

The adoption and education of sensor-based spraying technologies are key factors for widespread implementation. Farmers need to be aware of the benefits and potential of sensor-based systems to drive their adoption. Providing educational resources, training programs, and demonstrations can facilitate the understanding and acceptance of these technologies. Collaboration among research institutions, agricultural organizations, and industry stakeholders can help disseminate knowledge, promote best practices, and overcome barriers to adoption [225].

In conclusion, the future of sensor-based spraying in precision agriculture is promising. Standardization and interoperability efforts will ensure the seamless integration of sensor technologies. Advancements in sensor technology will enable more precise and reliable data acquisition. Enhanced data analytics and modelling techniques will provide valuable insights for decision-making. Finally, adoption and education initiatives will drive widespread implementation. By focusing on these future directions and opportunities, the full potential of sensor-based spraying in precision agriculture can be realised, leading to more sustainable and efficient farming practices.

VII. STATE OF THE ART AND FUTURE CHALLENGES

The contemporary landscape of precision delivery in agriculture is undergoing a transformative phase, marked by a confluence of technological innovations and automation strategies. This evolution is characterized by a strategic integration of advanced sensor technologies, robotic systems, and sophisticated data analytics, collectively reshaping the traditional paradigms of agricultural practices. Precision delivery, as a holistic concept, strives to optimize the deployment of agricultural resources, augment operational efficiency, and mitigate environmental impacts associated with conventional farming methods. The multifaceted nature of this emerging field encompasses several key dimensions, including a thorough examination of the precision agriculture market, the intricate design and development of robotic delivery systems tailored for both terrestrial and aerial platforms, the nuanced exploration of spray technologies with a keen focus on precision mechanisms, a detailed analysis of diverse spraying techniques informed by considerations of pest types and vegetation characteristics, and the ongoing refinement of sensor technologies to facilitate more accurate and targeted applications. This expansive overview underscores the interdisciplinary nature of precision delivery in agriculture, revealing a symbiotic integration of engineering, agronomy, and data sciences. Such convergence not only addresses contemporary challenges but also contributes substantively to the realization of sustainable and efficient agricultural practices in the modern era.

The evolution of precision delivery in agriculture, while promising, is not devoid of multifaceted challenges that merit careful consideration for the sustained advancement of this transformative field. A crucial facet is the ongoing refinement of sensor technologies to enhance their sensitivity, accuracy, and adaptability, thereby ensuring a level of precision that meets the nuanced demands of modern agricultural practices. Simultaneously, the potential environmental consequences stemming from increased automation, such as energy consumption and waste management, necessitate comprehensive assessments to develop strategies for mitigating ecological impacts. The establishment of robust regulatory frameworks emerges as imperative, aiming to strike a delicate balance between encouraging innovation and safeguarding against unintended consequences. Additionally, the integration of precision delivery technologies into diverse agricultural landscapes requires concerted interdisciplinary efforts, fostering collaboration between engineers, agronomists, environmental scientists, and policymakers to address the complex interplay of technological, environmental, and societal factors. Furthermore, issues surrounding data security and privacy gain prominence as interconnected systems become integral to precision delivery, urging the formulation of ethical guidelines and legal frameworks to safeguard sensitive information. Navigating these challenges collectively will be pivotal in shaping the trajectory of precision delivery in agriculture, ensuring its responsible and sustainable integration into future agricultural practices. Future research in precision spraying using robotics will likely focus on a few key aspects to improve these systems' effectiveness, sustainability, and adaptability in agricultural settings. Some of the potential areas include advanced sensing and data integration, real-time data processing for the possible use of edge computing, adaptive learning systems to improve spraying strategies over time based on feedback from previous applications, robotic autonomy, and collaborations to optimize the coverage area and minimize overlaps or gaps in spraying, human-robot interaction with user-friendly interfaces, and smart farming technologies for automated farming management systems can be the future scope of this area of research.

VIII. CONCLUSION

In conclusion, this review article highlights the transformative impact of mechanization, automation, and intensification on agricultural production, emphasizing the enhanced efficiency and precision of agricultural equipment with reduced reliance on human intervention. The escalating interest in agricultural robotics research and technologies emerges as a strategic response to the growing scarcity of skilled labor in crop production. The paper, designed to provide a systematic overview, delves into recent developments in precision delivery technology within agricultural robotics. The outlined focus areas encompass the precision agriculture market, design and development of spray robot technologies in terrestrial and aerial platforms, spray technologies and their mechanisms, diverse spraying techniques tailored to specific pests and vegetation, and the evolution of sensor technologies for precision spraying. This comprehensive overview not only captures the current landscape of agricultural robotics but also sheds light on the state-of-the-art robotic technologies employed in precision agriculture. The amalgamation of these advancements signifies a promising trajectory towards addressing challenges in contemporary agriculture, positioning robotics as a pivotal force in the optimization of agricultural processes.

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