Agriculture and Food

AIMS Agriculture and Food, 10(4): 885–916.
DOI: 10.3934/agrfood.2025046
Received: 20 August 2025
Revised: 12 November 2025
Accepted: 21 November 2025
Published: 04 December 2025

https://www.aimspress.com/journal/agriculture

Review

Field robots for precision agriculture

Antonio Comparetti[1,*], Adriano Fagiolini[2], Spyros Fountas[3] and Vincenzo Cascio[1]

[1] Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, Building 4, 90128 Palermo, Italy
[2] Department of Engineering, University of Palermo, Viale delle Scienze, Building 7, 90128 Palermo, Italy
[3] Department of Natural Resources & Agricultural Engineering, Smart Farming Technology Group, Agricultural University of Athens, Iera Odos, 75, 11855 Athens, Greece

* **Correspondence:** Email: antonio.comparetti@unipa.it; Tel: +3909123897057.

Abstract: In this review, a widely implemented method was followed. Therefore, the literature review process was divided into three phases: Planning, execution, and result analysis. Precision agriculture is a management strategy that takes into account the temporal and spatial variability to improve sustainability of agricultural production. The precision agriculture cycle is constituted by three stages: Geo-referenced measurement of within-field parameters; analysis and interpretation of geo-referenced data for mapping within-field parameters; and spatially variable rate crop input application. The instruments and techniques needed for implementing precision agriculture are Global Navigation Satellite Systems (GNSS), proximal and/or remote sensing, spatially-based software, soil-crop simulation models, controllers for spatially variable rate crop input application, guidance systems of agricultural machines, and field robots. During the precision agriculture cycle, instead of unmanned tractors or together with them, it is possible to use field robots for seeding and planting, plant protection, fruit harvest, and other crop operations. As a consequence of intensification, mechanisation, and automation, agricultural production has significantly increased over time. In both traditional and precision agriculture, the automation of crop operations is possible through the employment of robots, as they can accomplish repetitive labour tasks by keeping high precision, as well as saving time and energy during the working day. A total of 20 case studies of implementation of robots in agriculture and forestry were counted: Optimised coverage for arable farming; weed control; high precision seeding; crop yield estimation; precision irrigation; tree fruit production; vehicle formation control; date palm tree spraying; plant probing; cucumber harvesting; cucumber leaf removal; rose harvesting; strawberry harvesting; pot handling in nurseries and greenhouses; precision forestry; semi-automation of forwarder crane; livestock breeding and nurturing; livestock exploitation; livestock harvesting, slaughtering and processing; and aerial-based precision agriculture. In this review, Unmanned Ground Vehicles (UGVs) were classified according to different parameters and some examples were described for each category of agricultural UGVs or field robots. Precision agriculture will be widely implemented if cost-effective field robots are developed. From this study, it is possible to conclude that the most researched perception solutions are based on vision and cloud point sensors, and the UAV carrying some sensors is the preferred robotic solution for monitoring a large field, while a ground-based robot shows a unique design based on its required tasks. As such, agricultural tasks are becoming increasingly automated, above all in high-profit agriculture.

Keywords: precision farming; guidance systems of agricultural machines; unmanned tractors; agricultural robotics

1. Introduction

Precision agriculture, or precision farming, is the targeted application of crop inputs according to the locally determined crop needs [1–3]. As defined by the International Society of Precision Agriculture (ISPA) in January 2024, "Precision Agriculture is a management strategy that takes account of temporal and spatial variability to improve sustainability of agricultural production" [4].

The within-field spatial variability is the variation of the soil and/or crop parameters of a field, from a point to another of the field [3]. Traditional agriculture is based on the application of a spatially uniform rate of each crop input, thus causing high environmental impact and production cost. Precision agriculture takes into account the within-field spatial variability, so that it is based on spatially variable rate crop input application. The benefits of precision agriculture can be separated into three categories: Environmental (reduction of environmental impact, due to lower used amounts of crop inputs); energetic (reduction of consumed fuels and oil and, indirectly, reduction of used amounts of chemical fertilisers); and economical (improvement of quality and quantity production and, above all, reduction of the used amounts of crop inputs, that, together with the decreased used amounts of fuels and oil, results in the reduction of production cost) [3,5–7].

Farmers face many challenges: The need for competitive product prices on a global scale, creating constant pressure to reduce production costs; the need for more food by a quickly growing population, putting further pressure to increase crop yields; and a shortage of human work load.

In fact, ~7.6 billion people live on Earth, and it is estimated that by 2050, the world population will increase to 9.8 billion people, i.e., an increase of 28.94% [8]. The population growth challenges farmers to make changes in terms of control, monitoring, and management of crop operations, in order to satisfy the growing demand for food (requiring double the current food production for 2050) of high quality, because more people are looking for healthier foods that are free from herbicides and pesticides [9]. On the other hand, the global urbanisation process is transforming rural landscapes into urban ones, causing 68% of the population to reside in urban environments by 2050 [10]. As a consequence, farmers are looking for new methods of food production in increasingly smaller environments; in 1991, the percentage of world arable land was ~39.47% and in 2013, it was ~37.7%, which is a ~1.77% reduction in available arable land [9].

In this perspective, field robots are playing an important role in addressing these challenges, as they are stepping up and helping farmers improve efficiency and bring higher crop yields.

In fact, as a consequence of intensification, mechanisation, and automation, agricultural production has significantly increased over time. In both traditional and precision agriculture, the automation of crop operations is possible through the employment of robots, as they can accomplish repetitive labour tasks by keeping high precision, as well as saving time and energy during the working day [11,12].

Even if robots are used in a wide range of applications, agriculture and forestry have become top users of this new technology.

In fact, 20 case studies using robots in agriculture and forestry were counted: Optimised coverage for arable farming; weed control; high precision seeding; crop yield estimation; precision irrigation; tree fruit production; vehicle formation control; date palm tree spraying; plant probing; cucumber harvesting; cucumber leaf removal; rose harvesting; strawberry harvesting; pot handling in nurseries and greenhouses; precision forestry; semi-automation of forwarder crane; livestock breeding and nurturing; livestock exploitation; livestock harvesting, slaughtering, and processing; and aerial-based precision agriculture [13].

Field robots, that are different in their shape and function even within agriculture, are a type of professional service robots that automate manual tasks. They are typically used on land and operate in a fully autonomous way.

Bac et al. [14] analysed robots for harvest in the period between 1984 and 2014, while Oliveira et al. [15] studied ~21 robots.

Thus, the most essential information points about field robots for precision agriculture being described in this review are the following:

- History and current scenario of precision agriculture;
- Precision agriculture cycle;
- Instruments and techniques for precision agriculture;
- Assisted guidance systems of agricultural machines;
- Field robots for seeding and planting;
- Field robots for plant protection;
- Field robots for fruit harvest;
- Field robots for other crop operations;
- Conclusions and future directions.

2. Review methodology

The method proposed by Torraco [16], which is widely implemented, was followed. Therefore, the literature review process was divided into three phases:

- Planning (theoretical background);
- Execution (search strategy);
- Result analysis.

The first phase defines research questions and a transparent search strategy to select relevant studies [16].

We focused on the research question “Which robots help implement sustainable precision agriculture?” with the aim to recommend best farming practices for reducing the production cost and the environmental impact to enhance the farmer’s profit and preserve the soil quality, respectively.

Once that relevant information was extracted, it was summarised and discussed, and recommendations were put forward.

Thus, in the scope of this study, a systematic literature review of the robots for precision agriculture currently available was conducted. The Google search engine was used to source studies published from January 01, 2010 to November 9, 2025, using keywords describing the robots for precision agriculture, such as those reported in Table 1.

Table 1. Keywords used in the systematic review of robots for precision agriculture.

Keywords
Robots AND precision agriculture
Field robots AND precision agriculture
Robots AND precision farming
Field robots AND precision farming
Field robots
Agricultural robots

3. Precision agriculture cycle

Precision agriculture cycle (Figure 1) is constituted by the following three stages [3,5,6]:

1) Geo-referenced measurement of within-field parameters;
2) Analysis and interpretation of geo-referenced data for mapping within-field parameters;
3) Spatially variable rate crop input application [3,17,18].

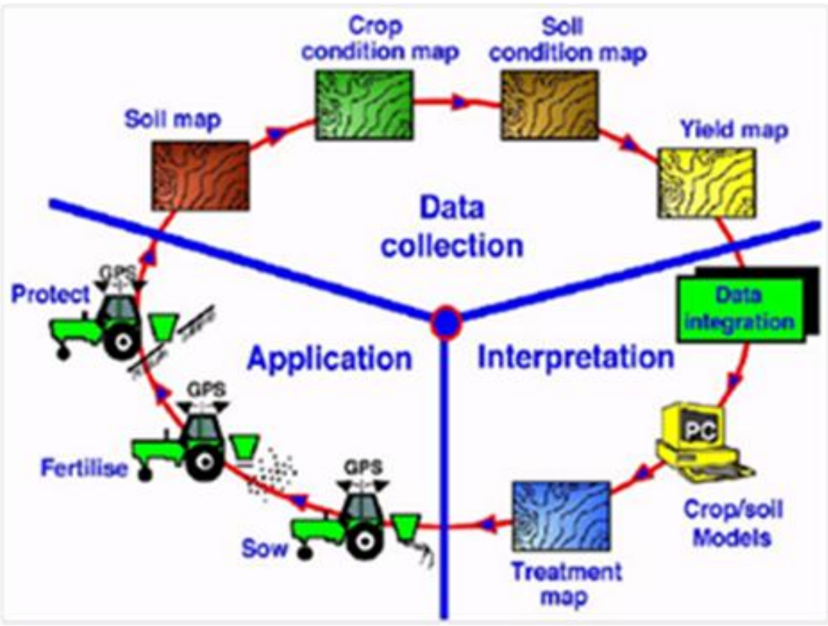

Figure 1. Precision agriculture cycle [3].

The geo-referenced measurement of within-field crop and soil parameters (stage 1) can be implemented by means of Global Navigation Satellite Systems (GNSS) and proximal sensors or remote sensing.

The analysis and interpretation of the several geo-referenced data of each crop or soil within-field parameter, i.e., big data (stage 2), is the most difficult challenge of precision agriculture. This phase is aimed at producing maps of within-field crop and soil parameters and, then spatially variable rate crop input application maps, by means of a Geographic Information System (GIS) [3]. During this phase, big data are processed by means of soil-crop simulation models and statistical and/or machine learning methods to extract patterns, insights, and statistical evidence, which will be useful for producing maps (e.g., weed density maps). Moreover, during this stage, the data acquired from sensors can be used for testing new soil-crop simulation models and/or check data drifts and/or classify the data. Furthermore, soil-crop simulations often require tested and reliable models for diagnosis that are based on sensed data and others, such as climate ones, and those sensed and recorded by meteorological stations, as well as the area production history.

The spatially variable rate crop input application (stage 3) includes not only the application of all crop inputs but also the spatially variable depth soil tillage. In fact, the within-field soil compaction can be significantly spatially variable, depending on the intensity and distribution of the traffic of agricultural machines and/or the action of tillage [19,20]. Therefore, the geo-referenced measurement of soil cone penetrometer resistance (index of soil compaction) is better if associated with soil water content and is needed for producing soil compaction maps [21–24]. Thus, in a soil compaction map, it is possible to identify different management zones (MZs) [25], where tillage methods can be planned [26]. As another option, a soil compaction map can be logged in the on-board PC of a tractor, linked with a tillage implement, in order to perform spatially variable depth soil tillage [27,28]: Soil will be tilled only in compacted areas and slightly below the depth of a compacted layer in order to remove soil pans, e.g., plough pan (Figure 2). Therefore, it is possible to reduce the draft force applied by the tractor and the used power, with a resulting decrease of used fuel and emitted Greenhouse Gases (GHGs), such as nitrous oxides and carbon dioxide.

Figure 2. System for setting up the working depth of a ripper to perform spatially variable soil tillage.

4. Instruments and techniques for precision agriculture

The instruments and techniques needed for implementing precision agriculture are listed in Table 2 [3,5,29].

Table 2. Instruments and techniques for implementing precision agriculture.

Instruments/techniques	Precision agriculture cycle stage
Global Navigation Satellite System (GNSS)	1,3
Proximal and/or remote sensing	1
Field robots	1,3
Spatially-based software and software for data interpretation	2
Soil-crop simulation models	2
Devices for setting up and controlling crop input application	3
Assisted guidance systems of agricultural machines	3

Initially, GNSS is needed to sense the position to which any measured within-field parameter must be tagged (stage 1) and where the rate of a crop input must be applied (stage 3) [3,30]. Proximal and/or remote sensing are techniques aimed at measuring within-field crop and soil parameters (stage 1) [3,30]. On-the-go or real-time proximal sensors are available for most crop and soil parameters and can be distinguished according to their working principle in five categories: Electrical or electro-magnetical; optical or radiometrical; mechanical; acoustic or pneumatic; and electro-chemical [31]. Sensors under development for weed detection vary from simple colour detectors to complex machine vision systems, aimed at using colour, shape, and texture of plant materials to distinguish weeds from crops and identify weed species. Remote sensing is a technique that can be carried out by means of UAVs or piloted aircrafts or satellites, according to the needed spatial resolution and the field area to be monitored. Remote sensing (e.g., from Copernicus Sentinel-2B satellite) provides big data about soils and crops. Thus, the proximal sensors of soil parameters can provide cheap spatially dense data that can be combined with the data produced by means of remote sensing, crop scouting, yield maps, and Digital Elevation Models (DEMs) in order to: Divide a field into MZs; drive soil sampling; and improve the accuracy of spatially variable rate crop input application maps.

Field robots can be useful for collecting fruits (temporally variable harvest), computing and recording the production of each plant (stage 1), and to automate soil sampling (stage 1), spatially variable crop operations (stage 3), and spatially variable rate crop input application (stage 3).

Spatially-based software (e.g., GIS) are needed to produce the maps of within-field crop and soil parameters and those for the application of spatially variable rates of crop inputs, while other software are fundamental for interpreting the measured data (stage 2) [3].

Soil-crop simulation models can be useful for identifying the causes of within-field spatial variability (stage 2) and for decision-making, i.e., producing increasingly accurate spatially variable rate crop input application maps [3]. Electronic devices for setting up and controlling the application of spatially variable rates of crop inputs (actuators or controllers) must be mounted on the agricultural machines used for crop operations (stage 3) [3,32]. Finally, assisted (semi-automatic or automatic) guidance systems of agricultural machines can be useful during crop operations (stage 3) [3].

5. Assisted guidance systems of agricultural machines

The modern assisted guidance systems of agricultural machines can be distinguished into two categories:

- Semi-automatic or free hands guidance systems;
- Automatic or autopilot guidance systems.

In a semi-automatic or free hands guidance system, the driver moves the steering wheel during the advance along a road, while an electrical pilot can move the steering wheel during a crop operation (Figure 3). This system enables the driver to pay attention to the working quality of the agricultural implement and increase the forward speed by 10–15% (e.g., during soil tillage by means of rotary tiller and seeding) [3].

Figure 3. Semi-automatic guidance system: (a) Ez-Guide computer; (b) controller and Ez-Steer electrical pilot; and (c) Ez-Steer electrical pilot, mounted on the steering wheel (Trimble) [3].

Automatic guidance systems (e.g., unmanned tractors) enable farmers to accurately follow planned trajectories along a field in order to perform offsets of the machine position and correct its steering angle (Figure 4) [3,33]. During a crop operation, a controller moves the steering wheel, the gearbox, the hydraulic lift, and the agricultural machine or implement linked with the tractor [3].

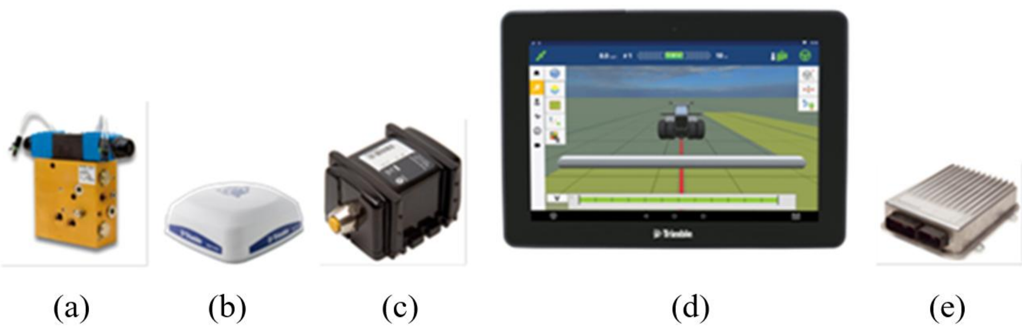

Figure 4. Automatic guidance system: (a) GNSS NAV-900 mobile receiver; (b) Autosense optical steering angle sensor; (c) GFX-750 computer; (d) Navigation Controller II; and (e) T3 electronic valve (Trimble) [3].

6. Unmanned tractors and field robots

Complex automatic guidance systems (e.g., unmanned tractors) enable farmers to accurately follow previously planned trajectories in a field to determine the offsets of machine position and correct its steering angle (Figure 5) [3,33–36].

Figure 5. An unmanned tractor is an agricultural machine equipped with an automatic guidance system, enabling the farmer to accurately follow previously planned trajectories in a field.

Unmanned tractors can be replaced by field (or agricultural) robots or work together with them. In fact, the major agricultural machinery manufacturers are mostly oriented towards the development of autonomous (or unmanned) tractors, i.e., machines that can emulate the conventional tractor without human intervention and control, and equipment that, although connected to a conventional tractor, is able to operate according to what it detects with a high degree of autonomy, such as the so-called "robotic implements" (field or agricultural robots). The large tractor and agricultural machinery industry seems to be more interested in the development of unmanned tractors (often driven by electric engines) rather than field robots. Therefore, this group of machines owns autonomy, as opposed to automatism, that belongs to field robots. By developing unmanned tractors, manufacturers are acquiring fundamental knowledge for innovation and preparing themselves for the mechanisation of tomorrow. However, the lack of legislations has discouraged the marketing of these machines, whose use is relegated to experimental companies. In fact, major tractor manufacturers, such as John Deere, Case IH, and Yanmar, or equipment manufacturers, such as Kuhn, despite having successfully developed unmanned tractors, do not plan to market them. This is because, although the technology is ready, legal constraints stemming from very incomplete legislation hinder the release of these autonomous wonders, especially in Europe [37].

Instead, in recent years, robotics is the newly emerging technology in precision agriculture, mainly because the automation of farming processes is saving time and energy required for performing repetitive farming tasks and increasing crop yield.

Several autonomously guided robots have been developed to carry out automatic weed control in the fields. Agricultural robots not only solve the problems of weed control but also perform the complex operations of precision agriculture to highly improve the crop yield. The robot navigates the field and interprets the assigned task. It helps farmers by eliminating weeds, applying chemicals, and harvesting the crops, and includes GNSS to locate themselves. It also employs cameras to pick up green plants from the soil. Moreover, the elimination of weeds is important, as weed growth reduces the crop yield by more than 50%. Hence, the robots are fitted with a precision spraying system that applies herbicides onto the weed plants. The use of sensors in this robot can also monitor the nutrient levels of plants and supply the required rates of fertilisers.

The major advantages of field (or agricultural) robots include: Limited mass and, therefore, weight, eliminating soil compaction; reduction of GHG (e.g., carbon dioxide) emissions; elimination of weeds; precise application of chemicals, which can contribute to reduce soil damage and water courses pollution; high accuracy (up to 2 cm, so that every seed can be precisely placed and mapped); support of multi-cropping practices that can contribute to natural pest control and improve biodiversity and crop yield; and scouting and crop care technologies, which can contribute to optimise irrigation and, therefore, increase water use efficiency.

Globally, the agricultural robot market is experiencing an increase in investments, due to the development of novel and technologically advanced robots. Agricultural robots or “agribots” are gradually being deployed across the world to help farmers and improve crop yield, by assisting in operations like harvesting and scouting. Harvest has been a mechanised process for a long time, and this trend continues across the world. Yet, for the most delicate crops, hand-picking dominates.

Based on the literature on agricultural robotics, two major solutions are identified:

- Unmanned Aerial Vehicles (UAVs), i.e., flying drones, equipped with sensors used at a distance (generally higher than 1 m) from the plants for remote sensing and certain basic crop management activities;
- Unmanned Ground Vehicles (UGVs) or ground rovers, equipped with sensors used closely to the plants (generally with a maximum distance of 1 m) for local monitoring and multi-task specialisation.

UGVs for precision agriculture can be classified according to their size in three types:

- Small electrically powered robots, able to perform only crop or soil monitoring and sensing tasks, due to their limited size and power; they are relatively cheap, more manoeuvrable, and can be adapted to a wide range of crops;
- Medium-size robots, that can generally both monitor field conditions through remote and proximal sensing and carry out crop operations, even if some of these, e.g., used in vineyards and orchards, are highly specialised and limited to very specific tasks; other robots are multi-purpose platforms designed to perform several crop operations;
- Robots of a size and power comparable to conventional tractors and other agricultural machines; the major agricultural machinery manufacturers add autonomous features to conventional agricultural tractors and combine harvesters; the automation of agricultural tractors and other machines has been done mainly by exploiting modern sensor-related technologies, e.g., machine vision, Real-Time Kinematic (RTK) GPS, and geometric direction sensors; systems like a controller (computer), i.e., a steering control device, as well as a localisation and a safety system are mounted on modern commercial tractors having ISOBUS control technology; newer vehicles are electrically powered but many current ones involve hybridisation, e.g., internal combustion diesel engine combined with electrical engine, to provide adequate power; these vehicles cause compaction and are relatively expensive, so they are cost-effective only in very large open fields [38].

UGVs can be classified according to the locomotion/mobility principle and kinematic architecture.

The locomotion/mobility principle refers to the way the platform interacts with the terrain to apply the draft force to the implement linked with it and to control the motion direction. From the motion point of view, the number of controllable degrees of freedom (DoFs) is equal to the total workspace DoFs, e.g., in UGVs the DoFs number is 3; an example is represented by legged robots that can freely move and rotate in any direction. Instead, the controllable DoFs are less than 3 in a tracked robot that can move forward/backward and rotate but cannot move sideways.

UGVs can be classified according to locomotion of ground mobile platforms in four major categories:

- Wheeled;
- Tracked;
- Legged;
- Hybrid, including legged-wheeled and tracked-legged systems [38].

The agricultural UGVs or field robots, that are generally wheeled or tracked [38], according to the performed tasks, can be classified as seven types [39], which are listed in Table 3.

Table 3. Classification of agricultural Unmanned Ground Vehicles (UGVs) or field robots [39].

UGVs	Applications	Tasks	Advantages
Field robots for nursery automation	Crop nurseries	Move plants in large greenhouses	Higher efficiency, addressing growing labour shortage
Field robots for seeding and planting	Mainly lettuce and vine crops	Accurately seed or transplant crops (equipped with 3D vision systems)	Optimal growth
Field robots for plant protection	Crop protection	Autonomously navigate a farm and spray targeted rates of herbicides or pesticides	Reduced crop exposure to herbicides and pesticides, prevention of growth of herbicide-resistant weeds or pesticide-resistant pathogens
Field robots for precision agriculture	Small farms or vineyards	Autonomously monitor soil macroporosity, photosynthetic activity, Leaf Area Index (LAI) and other biological parameters	Spatially variable management of crop operations
Field robots for fruit harvest	Fruit orchards	Identify and grasp fruits (equipped with 3D vision systems)	Faster harvest (sometimes completing the amount of work as ~30 operators)
Field robots for monitoring pollution	All crops	Measure GHGs (carbon dioxide and nitrous oxide) emissions	Reduced environmental footprints of agriculture
Field robots for livestock ranching	Livestock farms with large ranches	Herd livestock, monitor animals and ensure that they are healthy and have enough area to graze	Increased livestock health and optimised feeding

7. Field robots for seeding and planting

Among crop operations, seeding is a time-consuming and boring activity for farmers. Manual sowing is a highly inefficient process that requires a lot of human work load and can cause health problems for farmers, while mechanical seeding by means of a tractor and a seeder results in wasted seedlings. A low-cost agricultural robot was developed by Azmi et al. [40] for crop seeding. This prototype consists of two parts: A mobile base for robot movement and a seeding mechanism attached to the mobile base for seeds application. The mobile base has a four-wheel design to ease movement on uneven terrains, while the seeding mechanism is a crank-slider able to continuously inject seeds into the ground. Crop seeding tests showed that the robot can sow 138 seeds in 5 minutes, with an accuracy of 92%, compared to 102 seeds by human workers. This demonstrates an increase in the crop seeding efficiency higher than 35%. Moreover, the robot can work for up to 4 hours on a single battery charge. The recharging duration for the robot power supply is 1.5 hours. The prototype has successfully achieved its objective of reducing human interference, labour requirement, and the overall operating costs in agriculture for crop seeding by making the robot fully autonomous, using either a rail- or line-following system. However, an operator is required to manually steer the robot to each seeding path.

Moreover, transplanting is the most boring and time-consuming crop operation, which is mostly done manually. Many semi-automatic transplanters are developed but they demand manual labour for feeding seedlings into cups, resulting in reduced efficiency. Due to labour shortage during peak season, automation in transplanting is fundamental to ensure the timeliness of this crop operation. Thus, agricultural robots for planting may be an effective option for automatically transplanting nursery plants/seedlings [41]. In fact, they can carry out precision planting by ensuring optimal spacing and, therefore, increased crop yields. Thus, robots for planting reshaped traditional transplanting methodologies [42]. In the past decades, modern automatic machines for transplanting or transplanters were developed to replace humans to quickly and orderly remove seedlings from trays and transplant them in the fields. However, these machines for transplanting cannot identify the biological parameters of seedlings, so that the mechanised transplanting results in a lower amount of seedlings planted in the fields. The method of "planting robust seedlings and eliminating inferior seedlings" is difficult by a transplanter, thus causing a lower work quality in terms of higher missed planting and, therefore, a reduced crop yield. Li et al. [43] proposed a selective robot for transplanting and designed the Selective Intelligent Seedling Picking Framework (SISPF) based on deep learning. This robot is integrated with the mechanisms of seedling picking and dividing, as well as planting mechanisms. The field test showed that selective transplanting results in a missing planting of 2.13%, i.e. 9.91% lower than automatic transplanting.

Field robots for seeding and planting can be useful during stage 3 of precision agriculture cycle. In fact, the production of maps of (spatially variable) within-field parameters, decision-making, and spatially variable rate crop input application could be implemented in almost real time by using proximal sensors of crop and soil parameters, remote sensing, soil-crop simulation models, assisted guidance systems of agricultural machines, and field robots.

Thus, proximal sensors of within-field parameters and automatic guidance systems of agricultural machines also provide new opportunities for developing autonomous (unmanned) agricultural machines, integrating monitoring, decision-making, and spatially variable rate crop input applications. For example, ARVAtec FarmDroid FD20 is a field robot, having six or eight seeder components over six or eight rows to perform precision seeding, as well as herbicide spraying, between rows and within each row (Figure 6). This robot is equipped with four solar panels for its independent powering, a GPS mobile receiver, used in RTK mode, and a sensor of the application error during the crop operation. Based on the position of each sowed seed, the robot can also carry out herbicide spraying before weed emerging ("blind" herbicide spraying).

Two further innovations are added to this technology: They are embedded inside the same robot, making the machine revolutionary.

The first innovation is Dual Front Wheel (DFW), i.e., two front wheels instead of one. The two front wheels are mounted and aligned with the two rear wheels, so that the machine weight is better distributed on the wheels and, therefore, the soil compaction caused by the passage of the robot is reduced by 25%, rather than the model having three wheels.

The second innovation is Spot Application System (SAS), a system that enables farmers to apply a liquid chemical (fertiliser or herbicide or pesticide against insects) on the crop sowed by the robot and work during hoeing. This system is constituted by two tanks, each of 60 l volume for the chemicals to be applied; a pump; some pipelines for moving liquid chemicals to the rows; and nozzles, mounted on the working parts of the machine. The electrovalves commanded by the control unit of the robot enable the farmer to set up the treatment modes. The typical suggestion for localised spraying is an area of 6 × 6 cm. The working capacity is 15% higher than the previous model having one front wheel. As the area around the plant position is difficult to be subjected to hoeing, the SAS system can spray the herbicide where it is needed to treat the closest weeds. SAS can be used for both localised and strip spraying. Therefore, SAS increases the yield and reduces the cultivation cost, as the robot can carry out sowing and hoeing between rows and between plants, as well as spraying a fertiliser or herbicide or pesticide against insects. SAS can enable farmers to reduce the amounts of chemicals by 94% and, therefore, both the environmental impact and the cost of crop operations [44].

Figure 6. Field robot FarmDroid FD20 for precision seeding and herbicide spraying (ARVAtec) [44].

8. Field robots for plant protection

Field robots for weed and pathogen control can be useful during stage 3 of precision agriculture cycle and can be distinguished into two categories: Robots for mechanical weed control; and robots for chemical control of weeds and pathogens.

Among robots for mechanical weed control, Sportelli et al. [45] tested an autonomous All-Wheel Drive (AWD) mowing robot equipped with a GNSS (with RTK differential correction) for accurate navigation and ultrasonic sensors for obstacle avoidance. It can perform environmentally friendly weed control, i.e., mechanical mowing of inter-row and under-row areas in vineyards by means of a ventral cutting disc with razor blades. The robot autonomously operates within predefined boundaries, where metal wires were placed. Moreover, Zhao et al. [46] developed and evaluated an autonomous robot for mechanical weed control in strawberry fields. Based on the DIN-LW-YOLO model, this robot uses computer vision to detect strawberry seedlings, weeds, irrigation pipes, and weed growth points, enabling precise laser targeting. The robot achieves a 92.6% weed removal accuracy with a 1.2% crop damage rate.

Among robots for chemical control of weeds and pathogens, Fan et al. [47] developed a weed detection and target spraying wheeled robot for cotton fields that employs the CBAM module, BiFPN structure, and Bilinear interpolation algorithm to learn and distinguish weeds from cotton seedlings with an effective spraying rate of 98.93%. Moreover, Mohanty et al. [48] presented a robot designed for efficient herbicide application in rice fields using a YOLOv5-based machine learning framework. This robot integrates image recognition, AI-driven weed detection, and precise herbicide spraying to optimise weed control while minimising chemical use. Field tests demonstrated an accuracy of 98% in weed identification and a weed control rate of 95%, significantly outperforming traditional spraying. Furthermore, Liu et al. [49] developed and evaluated a spraying robot for orchards and nurseries. This robot is equipped with 3D-LiDAR for precise plant detection and uses a multivariable spraying model that adjusts flow rate, air volume, droplet size, and spray direction in real time. Test results demonstrate that this robot reduces chemical use by 83% compared to traditional spraying, while ensuring effective coverage and improved uniformity.

For example, Niqo RoboSpray of Niqo Robotics (India) is a spraying robot that can carry out herbicide or pesticide application in real time, because, in one passage, it senses the weeds or the crop plants attacked by a pathogen by means of a videocamera, selects the spots to be sprayed, and applies the herbicide or pesticide mixture (through independent nozzles) only in these spots (Figure 7). This robot enables farmers to save up to 60% of crop inputs, thus minimising the environmental impact of spraying [50].

Figure 7. Niqo RoboSpray of Niqo Robotics for herbicide or pesticide applications [50].

Moreover, EVO4 of Agri-EVE Corporate (Rovereto, Bolzano/Bozen, Italy) is an autonomous unmanned tractor that has a plug-in electrical engine and can be equipped with devices for harvest or actuators for spatially variable rate crop input application (Figure 8). Two versions are available: Base, having two electrical engines of 100 HP (~74 kW), powered by a battery of 40 kWh; and HP, having two electrical engines of 110 HP (~81 kW), powered by a battery of 50 kWh. This tractor is equipped with a hydraulic lift having a capacity up to 2400 kg and a Power-Take-Off (PTO) of 540 revolutions min^{-1} and can be linked with different implements and tools. Automated Driving System (ADS) enables the tractor to autonomously move by sensing and avoiding obstacles. The tractor is also equipped with ultrasound and infrared sensors, as well as a webcam and an engine controller, so that it can compute the minimum distance to be travelled towards the destination. This tractor is suitable for precision agriculture, because it includes software that collect and analyse the data measured by sensors, thus enabling it to perform spatially variable rate applications of herbicide or pesticide mixtures or fertilisers [51].

Figure 8. Unmanned tractor EVO4 of Agri-EVE Corporate for spatially variable rate crop input application [51].

Merlo Cingo M600A-e is the tracked unmanned electrical transporter that converts into a sprayer for vineyards (Figure 9). It was presented in June 2023 as a prototype and renewed. The new tracked transporter can autonomously spray between vineyard rows with high precision, within Viticoltura di Precisione - precision viticulture (Vi.P.) Project, to which Merlo is a partner. This project aims at making plant protection effective through the analysis of measured data by implying the use of a machine able to spray each plant (needing for specific spraying). Cingo M600A-e is powered by a pack of lithium ions batteries of 7.5 kWh providing energy to two electrical engines of 48 V, so that it has an autonomy of 4 hours and a recharge time of 3 hours. Thus, it can work by day and night within the row and inter-row for coming in and out from the row without needing an operator (autonomous guidance). The machine (generating zero emissions) is equipped with a pump having a flow rate of ~8l min^{-1} of biodegradable oil, which is needed to power the sprayer. The transporter is equipped with 360-degree sensors of environmental parameters, a smart unit for data analysis, and trajectory control, as well as a high precision GPS with RTK differential correction having a positioning error lower than 10 cm, so that the operator can log a track inside the vineyard to be travelled by the machine during crop operations. The used software was developed to keep Cingo equally far from the rows during spraying by stopping the travelling and the powering of the machine in the presence of obstacles. During the steering along the external bend, the GPS trajectory is followed, while eventual obstacles are avoided by following new tracks that, then, join the predefined trajectory. In the track, it is possible to include the approach to a recharge unit or a point for filling the sprayer tank with water. Moreover, the sprayer is autonomously powered by following start-points or end-points previously logged together with the track, so that the maximum accuracy and minimum waste are achieved. The tracked transporter is equipped with a fiberglass tank of 200 l volume, a diaphram pump, brass nozzles (with device avoiding drops), and a tangential fan. The transporter is suitable for rows of different width and in flat and sloping fields.

By using UAVs, multispectral data and innovative software, Vi.P. Project is aimed at introducing classification methods for identifying specific causes of stress by providing grapevine growers with a Decision Support System (DSS) able to highlight, in the MZs of the vineyard, the diseases, as well as nutrient and water deficiencies, to create maps for spatially variable rate crop input applications [52].

Figure 9. Tracked unmanned electrical transporter Merlo Cingo M600A-e that converts into a sprayer for vineyards [52].

9. Field robots for fruit harvest

Field robots can be used during stage 1 of precision agriculture cycle to collect fruits, by performing temporally variable harvest based on their ripeness, as well as calculating and recording the production of each plant. They can harvest fruits from continental (e.g., apple, pear, peach, plum, and apricot), Mediterranean (e.g., citrus species, grapevine, tomato, bell pepper, and strawberry), and tropical (e.g., coconut, kiwi, guava, lychee, mango, and avocado) plants. Indeed, harvesting fruits and vegetables is the most labour-intensive and time-consuming crop operation. With seasonal labour shortages of experienced workers, low harvest efficiency, food losses, and quality deterioration occur. In addition, emerging harvesting capabilities with high consistency and speed, along with the need to meet the ever-increasing demand for food, motivate the research of ground and aerial robotic monitoring and harvesting.

The use of robotic platforms for ground operations mainly includes fruit harvest. In this respect, studies have shown that robots can offer many benefits, including reduced labour costs, increased efficiency, and improved fruit quality [11,53]. However, there are several challenges that need to be addressed. One of the major challenges is the difficulty in developing robots that can accurately identify and pick ripe fruits, while avoiding damages to the fruit and plant [54]. Another challenge is the cost of developing and deploying these robots, which may not be feasible for small-scale farmers [55]. Researchers have made progress in addressing these challenges. For example, machine learning algorithms have been used to improve fruit detection and picking accuracy [56], as well as developing affordable robotic systems for small-scale farmers [57]. Overall, while there are challenges to overcome, the use of robots for fruit harvest holds a great promise for improving the efficiency and sustainability of crop operations.

More specifically, robotic manipulation of fragile products in unstructured environments is an open and challenging problem, so that the development of suitable end-effectors, as well as planning and control strategies, is required. There are different end-effectors used for fruit harvesting, including vacuum grippers, contact-grasping grippers, and robotic arms with cutting tools [58]. Among these, contact-grasping grippers having two or three fingers for fruit holding are the most commonly used types of end-effectors. Additionally, detachment methods such as grasp-and-twist, grasp-and-pull, and grasp-and-cut are used depending on the type of fruit. In some cases, additional sensors such as colour cameras and 3D sensors are used to improve fruit detection and localisation [55].

Vacuum grippers and suction cups are commonly used for handling fruits during packaging and transportation [59]. In addition, robotic arms with specialised end-effectors such as knives and peelers are used to perform further processing tasks such as peeling, slicing, and pitting. These systems can also be integrated with sensors and machine learning algorithms to optimise the processing and packaging workflow, based on the requirements of different fruit types. Some examples of fruit collection robots include the apple harvesting robot designed by Bulanon et al. [55] and the strawberry harvesting robot developed by Xiong et al. [60]. These robots use contact-grasping grippers to hold the fruit before it is detached, thereby minimising the risk of fruit damages.

Efficient handling and manipulation of harvested fruits are equally important as their collection [58]. Robotic systems can sort, classify, and package fruits based on their characteristics such as size, shape, and colour. Indeed, once the fruit is collected, it needs to be carefully handled and manipulated to avoid damages. Research has shown that soft robotics is a promising area for agricultural applications, as soft robots made of flexible materials can safely and gently interact with delicate crops [61]. This is achieved by active and online stiffness estimation [62], as well as decoupled and simultaneous control of the robot link position joint stiffness [63] to guarantee a proper mechanical impedance control at the fruit end. Soft robots can be used for tasks such as fruit picking and pruning, as well as improving efficiency [60]. Additionally, research has shown that automated grading and sorting systems can improve the accuracy and efficiency of fruit handling [58,64]. The research challenge here is to devise effective strategies that optimise the availability of a soft articulated robot arm, mounted aboard a mobile vehicle, that can exploit the large workspace obtained by the locomotion with the ability to gently handle the fruit and safely interact with farmers.

For all the above reasons, automation has so far mostly been applied to tomato [44,57,65] and apple harvesting, since they are common crops worldwide, and their fruits have a low variability in size and weight, are relatively hard, and, therefore, resistant to undesired impacts, as well as being easy to detect for their position in the crop, distinct colour, and shape. Finally, the circular structure of these fruits is simple, so that two or three fingers are enough to grasp them [66].

For example, GR-100 of Four Growers (USA) is a robot designed and built for working in greenhouses (Figure 10). This robot, equipped with eight videocameras (four of which are mounted on the robotic arm), can harvest, control the quality, and store the tomatoes at the speed of an operator, with high precision and an average harvest speed of 1 tomato s^{-1} and, therefore, 43 kg h^{-1} (average mass of fruit equal to 12 g). The robot, which can be remotely controlled by means of a dashboard platform, can harvest only tomatoes at a ripening stage of 98% (quality control). Almost 250 kg of tomatoes are transported during a working session [67].

Figure 10. Robot Four Growers GR-100 for tomato harvest inside greenhouses [67].

Moreover, Gus of Autopickr (UK) is a robot having a mass of 45 kg, is powered by a battery of 8–10 hours autonomy, and uses Ultra Wide Band (UWB) for asparagus harvest, in an open field or inside a greenhouse (Figure 11). This robot is equipped with a videocamera Intel Realsense and an arm (developed by ST Robotics) having an end-effector that works as a human hand by cutting and collecting the asparagus spears in a bin (until 20 kg), without catching them, preventing damaging the plants. Electrical engines transmit the motion to the arm by means of belts and pulleys [68].

Furthermore, Agrirobot is the project promoted by Gruppo di Azione Locale - Local Action Group (GAL) Terra è Vita of Bracigliano (Salerno, Italy), jointly with the company Italrobot srl (former Tea Impianti srl), Consiglio per la Ricerca in Agricoltura e l’Analisi dell’Economia Agraria - Council for Agricultural Research and Economics, i.e., Dr. Marcello Biocca (CREA) and the farm Cosoni of Campania region (Italy).

Figure 11. Robot Gus of Autopickr for asparagus harvest [68].

This robot is constituted by an unmanned shuttle powered by a battery of 48 V voltage, having an autonomy of ~8 hours and can move between the crop rows and come back to the recharge base when needed (Figure 12). The shuttle is equipped with an arm similar to a human one with 6 freedom degrees and a grasp system shaped as a shear that can cut the stalk of strawberry and release it in a bin mounted on the robot. In order to recognise the ripened fruits to be harvested, this robot is equipped with a RGB videocamera and can collect 2 strawberries min^{-1}, for a total of ~16,000 strawberries week^{-1} (~19 hours day^{-1} per 7 days), while an operator can collect from 10,000 to 33,000 strawberries week^{-1} [69].

Figure 12. Robot developed within the Agrirobot project for strawberry harvest [69].

A second major use of field robots comprises aerial machines that can be deployed for crop monitoring. For example, Tevel company manufactures and commercialises Flying Autonomous Robots, driven by cutting-edge guidance and control Artificial Intelligence (AI) perception (machine vision) algorithms that enable high accuracy and maneuverability (Figure 13). These field robots collect harvest data (i.e., total amount of picked fruits, weight and size of each fruit, fruit ripeness based on colour grading, time label, position, distribution of weight in the plant, and size and colour of fruits in the bin) in real time for each single fruit they pick. These durable and light robots enable harvesting a wide range of fruits, from a 50 g apricot to a 700 g apple. At world level, the Flying Autonomous Robot is the only one having no harm but it can physically interact with plant foliage [70].

Figure 13. Flying Autonomous Robot for collecting apple fruits (Tevel) [70].

10. Field robots for other crop operations

Field robots can also be used for other crop operations, within both traditional and precision agriculture.

In fact, field robots can be used during stage 1 of precision agriculture cycle for automated soil sampling and monitoring activities.

For example, the AutoProbe developed by AgRobotics is a precision agriculture robotic system that offers modern soil services to increase the cost savings and crop yield (Figure 14). It also provides efficient, consistent, and accurate soil analysis, compared to any other commercially available equipment. This automated system features a 6 inch (~15 cm) deep probe and collects samples in a shorter time than semi-automatic or manual sampling. The key benefits of AutoProbe include: Capacity of sampling 150 acres (~61 ha) h^{-1}; generation of a quality sample every 45 s and its transmission to cab; increase of crop yield; and low cost [71].

As another example, the robot Black Shire RC3075 (Figure 15) can be equipped with different implements and was built in Vezza d'Alba (Cuneo, Italy) in 2020 as a multi-tasking, autonomous, and remotely controlled machine, which can also work in vineyards having a slope up to 65% (for up-down crop operations) and up to 50% (for crop operations along the field contours). The robot has a total mass of 3650 kg, an engine Kubota Stage V having size of 3000 cm^3, power of 75 HP (~55 kW), and two synchronous AC electrical engines powering two tracks having high draft force Camso CTL CD, ensuring maximum adherence and minimum soil compaction. This robot has two working modes for front and rear hydraulic lifts: "pressure", whereas the pressure is automatically set up according to the soil slope, thus enabling the linked implement to be held into contact with the ground; and "position", whereas the implement is kept blocked at the selected height. The robot has two driving modes for suspensions: “standard”, where they work under pressure or in stiff position; and “smart”, suitable for manoeuvres on headland, because the mass of the internal track is limited during steering. This robot, equipped with a hydraulic system having flow rate of 60 $l\,min^{-1}$ for traditional implements, can be used in an autonomous way or controlled by means of a remote control with a screen or an app for smartphones. Thus, it is possible to monitor the hydraulic pressure and the cooling pressure on the machine or using this app, as well as carry out the diagnostics for sensing eventual failures. The robot is equipped with a GNSS receiver with satellite antenna to compute its position and trajectory with centimetre-level accuracy (using RTK differential correction) [72].

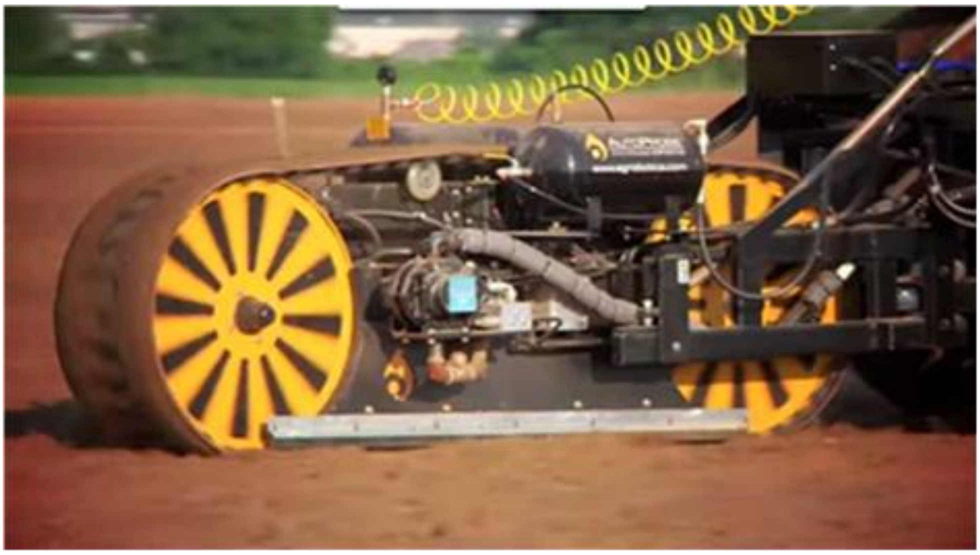

Figure 14. AutoProbe of AgRobotics for automated soil sampling [71].

Figure 15. Robot Black Shire RC3075 for vineyard crop operations [72].

As a further example, Hammerhead FR-01 is a robot that can be equipped with different implements and was developed by the startup Field Robotics, spin-off of the University of Bologna (Italy), and is suitable for any crop operation between the vineyard rows (Figure 16). The robot has two electrical engines, Bonfiglioli, each of 5 kW power, and an internal combustion engine of 10 kW power, to activate the PTO of 540 and 1000 revolutions min^{-1}, enabling it to transmit motion to sarment choppers, sprayers, and agricultural implements, as well as a three-point hitch. The compact sizes (length of 3.2 m and width of 1.4 m), besides a steering radius of 2 m, enabled by the tracks, make the robot easily manoeuvrable and suitable also for sloping mountain areas by minimising soil compaction. In fact, the robot has a mass of only 795 kg and a loading capacity of 1000 kg. The sprayer tank, the frame for placing the boxes for fruit harvest, etc. can be fixed on the upper platform, having six linkage points. The driving of this robot can be remotely controlled or autonomous. The latter driving can be in one of two navigation modes: “open field”, where the robot can autonomously reach the field by using GPS signals with RTK differential correction and videocameras; and “row”, where it works on the field using a LIDAR sensor and videocameras [73].

Figure 16. Robot Hammerhead FR-01 developed by the startup Field Robotics for vineyard crop operations [73].

Moreover, Bakus of VitiBot (Champagne region, France) is an autonomous tractor or overstepping robot, available in two models, 3.5 m long, and having a mass of 2500 kg (Figure 17): P75S, 1.75 m wide and 2 m high, for narrow vineyards; and P75L, 1.95 m wide and 2.5 m high, for large vineyards. Bakus has electrical engines; the L model has 4 independent electrical engines, powered by four lithium ions batteries for four steering wheels, with energy recovery during coming down (consumption of 60 kWh, maximum autonomy of ~12 hours and recharge time of ~2 hours). Bakus is equipped with two GPS receivers (with RTK differential correction) that enable work with centimetre-level positioning accuracy, in any visibility condition, and can be linked with two implements per side for soil tillage, herbicide, and pesticide spraying [74].

Figure 17. Bakus robot of Vitibot for vineyard crop operations [74].

Furthermore, AIgro UP is a super compact and electrical robot of the start-up AIgro (The Netherlands) that can be used between rows for different crop operations such as pruning (by means of a cutting bar), herbicide spraying, monitoring, and data collection (Figure 18). The robot is 1.35–1.55 m long, 0.55 m wide, 0.61 m high, and has a mass of 75 kg, so that it can work also on wet soils. It is powered by two lithium ions batteries of 48 V voltage having autonomy of 8–10 hours and recharge time of ~4 hours, at a maximum forward speed of 3.6 km h^{-1} (1 m s^{-1}) and working width of 0.6 m (working capacity of 15 ha $week^{-1}$). The robot easily moves with high precision between rows, in an autonomous way, because it is equipped with two GPS receivers (with RTK differential correction), proximity sensors, and Wi-Fi connectivity [75].

Figure 18. AIgro UP robot for crop operations in open field, tunnels, and greenhouses [75].

Moreover, BoniRob, developed by Amazone-Werke, in association with Robert Bosch GmbH, Osnabrück University of Applied Sciences and other partners, is an autonomous field robot that is equipped with a GPS and sensors with spectral imaging technology (Figure 19). The robot includes a quick-change device for use in sensors and a chassis with an individual wheel drive. This provides many options, including track widths between 0.75 and 2 m and adjustable ground clearance between 0.4 and 0.8 m. It can independently navigate and sense the GPS position of individual plants before mapping and recording the locations. This system can automatically and continuously determine and monitor the growth states of plants. The major advantages of BoniRob include: Automatic acquisition of the measured data of many plants; high efficiency; rapid output production; weed elimination; and a selective application of fertiliser [76].

Figure 19. BoniRob robot, developed by Amazone-Werke, in association with Robert Bosch GmbH, Osnabrück University of Applied Sciences and other partners [76].

Furthermore, Zilus of Sabi Agri (France) is an electrical field robot for crop operations in vineyards and other fruit tree orchards. It has a resistant steel frame, can work above plants (overstepping) or between rows, because of the minimum width of 1.50 m, is equipped with an electrical PTO, and can be linked with electrical, mechanical, and hydraulic implements and tools to be fixed on its front, side, and rear parts. The tracks and the mass of 2 t ensure adherence without soil compaction and cause Zilus to also work on sloping soils.

This robot has four driving modes: Autonomous by means of GPS signals; activated by means of remote control; by means of optional and removable driving cab; and coordinated with the electrical tractor Alpo (Robotic Agreement).

Furthermore, Alpo of Sabi Agri is an electrical overstepping tractor of 50 HP (~37 kW) power, powered by a battery of 41 kWh having a maximum autonomy of ~10 hours and a recharge time of ~2 hours. A solar panel having 3 m^2 surface, on the roof, gives an extra autonomy up to 15%. Four drive wheels enable Alpo to carry out soil tillage and other crop operations. This tractor, which can be equipped with mechanical, electrical, and hydraulic implements, has a very low centre of gravity, so that it can work with a maximum slope of 35%. Alpo, which is suitable for large and narrow plant distances, has a mass of ~2 t and low-pressure tyres, thus minimising soil compaction.

Aboard the electrical tractor Alpo, the operator can command the robot Zilus, so that they can go forward and work in synergy with different implements, in one passage, optimising working quality and times (Figure 20) [77].

Figure 20. Electrical overstepping tractor Alpo (left) and electrical overstepping robot Zilus (right) of Sabi Agri for carrying out crop operations in synergy in a vineyard (here) or another fruit tree orchard [77].

Finally, the Indian company Farmrobo Technologies, thanks to the collaboration among Indian and Hungarian engineers, produced the compact robot iMog, which is suitable for small farms (Figure 21).

iMog is 0.61 m wide, 0.76 m high, and 1.22 m long, so that it is one of the most compact machines in the world. These so small sizes make this robot work where traditional machines cannot fit or can damage the crops. Furthermore, the mass of 250 kg minimises the soil compaction.

The development of iMog began in 2019 and produced a multifunctional machine that can carry out several tasks. The robot is equipped with an electrical engine of 8 HP, powered by a lithium ions battery LFP of 90 A h^{-1}. This power is enough to manage the available agricultural machines (connected to a PTO) and implements, i.e., rotary tiller, plough, harrow, high-tech mist blower, and shredder. iMog has an autonomy of 4–5 hours and a recharge time of 2.5–3 hours. The electrical robot of Farmrobo Technologies can also work in indoor environments, such as greenhouses.

iMog is a robot that can work by following specific tracks, thanks to GPS guidance (with RTK differential correction), that enables the machine to move with a centimetre-level positioning accuracy. Moreover, iMog uses an algorithm for keeping the row powered by AI and aided by a videocamera that lets it keep an optimum guidance in difficult conditions. The farmer must only plan the tracks by using a map and a controller, enabling iMog to follow these tracks. As far as safety, the robot can sense obstacles and has an automatic stopping system.

Besides unmanned guidance, the robot of Farmrobo Technologies can be controlled by means of a radio remote control, enabling the farmer to guide iMog in difficult areas.

Farmrobo iMog is available only in India and the Middle East but it should be exported soon to Europe. Approximately 20 iMog were working at the end of 2024.

According to the web-site specialised in agricultural robotics Future Farming, the robot has a price of ~€ 12,000, plus agricultural machines and implements: € 1600 for rotary tiller; € 700 for plough or harrow; € 1000 for mist blower; and € 1300 for shredder [78].

Figure 21. Electrical robot iMog of Farmrobo Technologies during spraying by means of a mist blower [78].

The major characteristics of the field robots usable for implementing precision agriculture are summarised in Table 4.

Table 4. Major characteristics of the field robots for precision agriculture.

Manufacturer	Model	Applications	Tasks	Advantages
ARVAtec	FarmDroid FD20	Row crops	Seeding, fertiliser or herbicide or pesticide application during hoeing	Reduction of chemical amounts by 94%
Niqo Robotics	Niqo RoboSpray	All crops	Herbicide or pesticide application	Saving of chemical amounts by up to 60%
Agri-EVE Corporate	EVO4	All crops	Herbicide or pesticide or fertiliser application	Saving of chemical amounts
Merlo	Cingo M600A-e	Vineyards	Pesticide spraying	Spatially variable rate pesticide application
Four Growers	GR-100	Greenhouses	Tomato harvest	Harvest of 43 kg h^{-1} of 12 g fruits
Autopickr	Gus	Open fields and greenhouses	Asparagus harvest	No plant damage

Continued on the next page

Manufacturer	Model	Applications	Tasks	Advantages
Italrobot	Agrirobot	Greenhouses	Strawberry harvest	Harvest of 16,000 strawberries $week^{-1}$
Tevel	Flying Autonomous Robots	Fruit orchards	Fruit harvest	Harvest of fruits having mass from 50 g (apricot) to 700 g (apple)
AgRobotics	AutoProbe	All crops	Soil sampling and analysis	Sampling of 61 ha h^{-1}
Black Shire	RC3075	Vineyards	Various crop operations according to the implement	Work in soils having slope up to 65% (up-down) and 50% (along field contours)
Field Robotics	Hammerhead FR-01	Vineyards	Sarment chopping, spraying, etc., according to the implement	Minimum soil compaction
VitiBot	Bakus	Vineyards	Soil tillage, herbicide and pesticide spraying, according to the implement	Capacity to work overstepping, linkage with two implements per side
AIgro	AIgro UP	Row crops	Pruning, herbicide spraying, etc., according to the implement	Working capacity of 15 ha $week^{-1}$
Amazone-Werke	BoniRob	All crops	Monitoring the growth states of plants	Acquisition of the measured data of many plants, high efficiency, rapid output production, weed elimination, selective fertiliser application
Sabi Agri	Zilus	Vineyards and other fruit orchards	Various crop operations according to the implement	Capacity to work overstepping or between rows, linkage with implements on front, side and rear parts, no soil compaction
Sabi Agri	Alpo	Vineyards and other fruit orchards	Soil tillage and other crop operations, according to the implement	Capacity of working overstepping, also in soils having slope up to 35%, minimum soil compaction
Farmrobo Technologies	IMog	Open fields and greenhouses	Soil tillage, pesticide spraying, shredding, etc., according to the implement	Minimum soil compaction

11. Conclusions and future directions

In the future, precision agriculture could be implemented on a larger scale if the following requirements are satisfied [3,5]:

1) Quantifying its economic and environmental benefits;
2) Developing user-friendly software for processing and interpreting the measured geo-referenced data (big data);
3) Developing soil-crop simulation models, in order to identify the causes of within-field spatial

variability and, therefore, adjust the crop input rates from the next growing season [3];

4) Developing cost-effective field robots, in order to perform automated crop operations, including temporally variable fruit harvest and spatially variable rate crop input application.

In agreement with Botta et al. [11], from this study, it is possible to conclude that:

- The most researched perception solutions are those based on vision and cloud point sensors, often combined with machine learning approaches to interpret the collected big data;
- The UAV is the preferred robotic solution when a large field (generally less than 5 ha) must be monitored, but it is just a conventional UAV carrying some sensors;
- A ground-based robot (Unmanned Ground Vehicle - UGV) shows a unique design based on its required tasks;
- Most ground-based robots are small ones, only dedicated to monitoring activities;
- Agricultural tasks are becoming increasingly automated, above all in vineyards and other fruit orchards, as well as for other high-value agricultural products.

In precision agriculture, many measurements are carried out at different spatial scales (from single plants to whole fields) and in different times during the growing season. Precision agriculture and the use of GNSS for agricultural machines provide location and time information of all crop input applications.

The discussion on the challenges and future perspectives highlights the significance of integrating agronomy and biomimetics, big data, and AI, digital twinning, and human-machine interaction.

The advancement in these sectors not only triggers the progress of robotic arm technology but also introduces more innovative and efficient solutions in precision agriculture. The application of robotic arms in precision agriculture demonstrates a huge potential and a broad horizon. With continuous technological advancements and innovations, robotic arms can play an increasingly pivotal role in future precision agriculture [79].

The integration of AI and robotics has significantly enhanced the capabilities of precision agriculture. In fact, AI and robotics carry out a key role in precision agriculture, as they contribute to data-driven decision-making, automated crop operations, and more efficient and sustainable farming practices. The synergy between AI algorithms, advanced sensors, and robotic platforms enables real-time data collection, analysis, and targeted interventions, thus fostering efficient resource management and increased crop yield.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

Antonio Comparetti: Conceptualization, supervision, investigation, methodology, writing—original draft, writing—review and editing; Adriano Fagiolini: Conceptualization, investigation, data

curation, writing—original draft; Spyros Fountas: Conceptualization, methodology, data curation; Vincenzo Cascio: Data curation, formal analysis, validation.

References

1. Paice MER, Day W (1997) Using computer simulation to compare patch spraying strategies. In: Stafford JV (Ed.), *Precision Agriculture '97: Spatial Variability in Soil and Crop,* Oxford, BIOS Scientific Publishers, 1: 421–428.
2. McGovern EA, Holden NM, Ward SM, et al. (1998) Calibration of Landsat Thematic Mapper imagery for milled peat density prediction. Jyvaskyla, Finlandia.
3. Comparetti A (2023) Fundamentals of Precision Agriculture. Encyclopedia. Available from: https://encyclopedia.pub/entry/40241.
4. ISPA—International Society of Precision Agriculture (2024) Precision Agriculture Definition. Available from: https://www.ispag.org/resources/definition.
5. Comparetti A (2011) Precision agriculture: Past, present and future. In: *Proceedings of the International scientific conference Agricultural Engineering and Environment—2011 Agroinzinerija ir energetika Nr. 16-2011*, key-note presentation, Akademija, Kaunas district, Lithuania, 216–230.
6. Shaheb MR, Sarker A, Shearer SA (2022) Precision agriculture for sustainable soil and crop. In: Aide M, Braden I (Eds.), *Soil Science—Emerging Technologies, Global Perspectives and Applications,* InTechOpen, 2022: 1–292.
7. Erickson B, Fausti SW (2021) The role of precision agriculture in food security. *Agronomy* 113: 4455–4462. https://doi.org/10.1002/agj2.20919
8. United Nations (2017) World Population Projected to Reach 9.8 Billion in 2050. Available from: https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html.
9. Oliveira LFP, Moreira AP, Silva MF (2021) Advances in agriculture robotics: A state-of-the-art review and challenges ahead. *Robotics* 10: 52. https://doi.org/10.3390/robotics10020052
10. United Nations (2018) World Urbanization Prospects: The 2018 Revision. *Econ Soc Aff* 1: 1–2.
11. Botta A, Cavallone P, Baglieri L, et al. (2022) A review of robots, perception, and tasks in precision agriculture. *Appl Mech* 3: 830–854. https://doi.org/10.3390/applmech3030049
12. Fountas S, Mylonas N, Malounas I, et al. (2020) Agricultural robotics for field operations. *Sensors* 20: 2672. https://doi.org/10.3390/s20092672
13. Bergerman M, Billingsley J, Reid J, et al. (2016) Robotics in agriculture and forestry. In: Siciliano B, Khatib O (Eds), *Springer Handbook of Robotics*, Cham: Springer International Publishing (Springer Handbooks), 1463–1492. https://doi.org/10.1007/978-3-319-32552-1_56
14. Bac CW, Henten EJv, Hemming J, et al. (2014) Harvesting robots for high-value crops: State-of-the-art review and challenges ahead. *J Field Robot* 31: 888–911. https://doi.org/10.1002/rob.21525
15. Oliveira LFP, Silva MF, Moreira AP (2020) Agricultural robotics: A state of the art survey. In: *Proceedings of the 23rd International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2020),* Moscow, Russia, 279–286.
16. Torraco RJ (2005) Writing integrative literature reviews: Guidelines and examples. *Hum Resour Dev Rev* 4: 356–367. http://dx.doi.org/10.1177/1534484305278283

17. Molinelli G (1993) Rilievi topografici con tecniche satellitari (Topographic survey using satellite techniques). *Geoinforma-Topografia Fotogrammetria. Euromail* (appendix) 70: 2–4 (in Italian).
18. Comparetti A (1999) Soluzioni innovative per la meccanizzazione agricola: i sistemi di posizionamento (Modern solutions for agricultural mechanisation: positioning systems), PhD dissertation, 1–173 (in Italian).
19. Mouazen AM, Ramon H, De Baerdemaeker J (2001) On-line detection of soil compaction distribution based on finite element modelling procedure. In: Grenier G, Blackmore S. (Eds.), *Proceedings of the 3rd European Conference of Precision Agriculture*, Montpellier, France: Agro Montpellier, Ecole Nationale Supérieure Agronomique de Montpellier, 455–460.
20. Alaoui A, Diserens E (2018) Mapping soil compaction—A review. *Curr Opin Environ Sci Health* 5: 60–66. https://doi.org/10.1016/j.coesh.2018.05.003
21. Carrara M, Castrignanò A, Comparetti A, et al. (2005) Multivariate geostatistics for assessing and predicting soil compaction. In: *Proceedings of the 5th European Conference on Precision Agriculture (5ECPA)*, Uppsala, Sweden, 723–730.
22. Carrara M, Castrignanò A, Comparetti A, et al. (2007) Mapping of penetrometer resistance in relation to tractor traffic using multivariate geostatistics. *Geoderma* 142: 294–307. https://doi.org/10.1016/j.geoderma.2007.08.020
23. Comparetti A, Febo P, Orlando S (2011) A system for the real-time geo-referenced measurement of soil parameters. In: *Rural Development in Global Changes*, Book 1, 5th International Scientific Conference "Rural Development 2011", Akademija, Kaunas district, Lithuania, 319–323.
24. Comparetti A, Febo P, Orlando S (2013) A system for the real-time geo-referenced measurement of soil parameters. *Bulg J Agric Sci* 19: 1253–1257.
25. Alesso CA, Masola MJ, Carrizo MA, et al. (2019) Spatial variability of short-term effect of tillage on soil penetration resistance. *Archives Agron Soil Sci* 65: 822–832. https://doi.org/10.1080/03650340.2018.1532076
26. Mzuku M, Khosla R, Reich R, et al. (2005) Spatial variability of measured soil properties across site-specific management zones. *Soil Sci Soc Am J, Soil Fertil Plant Nutr* 69: 1572–1579. https://doi.org/10.2136/sssaj2005.0062
27. Adamchuk VI, Skotnikov AV, Speichinger JD, et al. (2003) Instrumentation System for Variable Depth Tillage. 2003 ASAE Annual International Meeting. Paper Number 031078, Las Vegas, Nevada, USA, 1–10.
28. Whattoff D, Mouazen A, Waine T (2017) A multi sensor data fusion approach for creating variable depth tillage zones. *Adv Anim Biosci* 8: 461–465. https://doi.org/10.1017/S2040470017000413
29. Erickson B, Fausti S, Clay D, et al. (2018) Knowledge, skills, and abilities in the precision agriculture workforce: An industry survey. *Nat Sci Educ* 47: 1–11. https://doi.org/10.4195/nse2018.04.0010
30. Comparetti A (2000) L'elettronica per l'agricoltura di precisione (The electronics for precision agriculture). *Macchine e Motori Agricoli* 2: 74–82 (in Italian).
31. Adamchuk VI, Hummel JW, Morgan MT, et al. (2004) On-the-go sensors for precision agriculture. *Comput Electron Agric* 44: 71–91. https://doi.org/10.1016/j.compag.2004.03.002
32. Felton WL, Alston CL, Haigh BM, et al. (2002) Using reflectance sensors in agronomy and weed science. *Weed Technol* 16: 520–527. https://doi.org/10.1614/0890-037X(2002)016[0520:URSIAA]2.0.CO;2

33. Dobermann A, Blackmore S, Cook SE, et al. (2004) Precision farming: Challenges and future directions. In: *Proceedings of the 4th International Crop Science Congress*, Brisbane, Australia.
34. Batte MT, Ehsani MR (2006) The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. *Comput Electron Agric* 53: 28–44. https://doi.org/10.1016/j.compag.2006.03.004
35. Bora GC, Nowatzki JF, Roberts DC (2012) Energy savings by adopting precision agriculture in rural USA. *Energy, Sustainability and Society* 2: 1–5. Available from: http://www.energsustainsoc.com/content/2/1/22.
36. Kvíz Z, Kroulik M, Chyba J (2014) Machinery guidance systems analysis concerning pass-to-pass accuracy as a tool for efficient plant production in fields and for soil damage reduction. *Plant, Soil Environ* 60: 36–42. https://doi.org/10.17221/622/2012-PSE
37. Benvenuti L (2024) Robotic equipment and autonomous tractors. Agri Machines World. Available from: https://www.agrimachinesworld.com/2024/06/12/robotic-equipment-and-autonomous-tractors/.
38. Vidoni R, Carabin G, Quaglia G, et al. (2024) Advances in mobility platforms for agricultural robots (e-chapter). In: van Henten E, Edan Y (Eds.), *Advances in agri-food Robotics*, Burleigh Dodds Series in Agricultural Science: 323–354, Burleigh Dodds Science Publishing, Cambridge, UK. http://dx.doi.org/10.19103/AS.2023.0124.08
39. Rajmane R, Gitay N, Yadav A, et al. (2020) Precision agriculture and robotics. *Int J Eng Res Technol* 9: 17–22. https://doi.org/10.17577/IJERTV9IS010019
40. Azmi HN, Sami SHH, Gsangaya KR, et al. (2023) Design and fabrication of an agricultural robot for crop seeding. In: *Materials Today: Proceedings,* 81: Part 2: 283–289. https://doi.org/10.1016/j.matpr.2021.03.191
41. Khadatkar A, Sawant CP, Magar AP, et al. (2025) Agricultural robots and automated machinery for handling of nursery seedlings with special reference to the transplanting devices. *Discov Appl Sci* 7: 916. https://doi.org/10.1007/s42452-025-06736-5
42. Prajyendu, Sharmab H, Kuntal P (2020) Agricultural robots for harvesting and planting. *Turkish J Comput Math Educ* 11: 1112–1118. https://doi.org/10.61841/turcomat.v11i1.14410
43. Li M, Zhu X, Ji J, et al. (2025) Visual perception enabled agriculture intelligence: A selective seedling picking transplanting robot. *Comput Electron Agric* 229: 109821. https://doi.org/10.1016/j.compag.2024.109821
44. ARVAtec - Agricoltura di Precisione (2025) FarmDroid FD20. Available from: https://www.arvatec.it/prodotti/farmdroid/fd20/.
45. Sportelli M, Frasconi C, Fontanelli M, et al. (2021) Autonomous mowing and complete floor cover for weed control in vineyards. *Agronomy* 11: 538. https://doi.org/10.3390/agronomy11030538
46. Zhao P, Chen J, Li J, et al. (2025) Design and testing of an autonomous laser weeding robot for strawberry fields based on DIN-LW-YOLO. *Comput Electron Agric* 229: 109808. https://doi.org/10.1016/j.compag.2024.109808
47. Fan X, Chai X, Zhou J, et al. (2023) Deep learning based weed detection and target spraying robot System at seedling stage of cotton field. *Comput Electron Agric* 214: 108317. https://doi.org/10.1016/j.compag.2023.108317

48. Mohanty T, Pattanaik P, Dash S, et al. (2025) Smart robotic system guided with YOLOv5 based machine learning framework for efficient herbicide usage in rice (*Oryza Sativa* L.) under precision agriculture. *Comput Electron Agric* 231: 110032. https://doi.org/10.1016/j.compag.2025.110032
49. Liu H, Du Z, Shen Y, et al. (2024) Development and evaluation of an intelligent multivariable spraying robot for orchards and nurseries. *Comput Electron Agric* 222: 109056. https://doi.org/10.1016/j.compag.2024.109056
50. Niqo Robotics (2025) Spot spraying robot Niqo RoboSpray™ helps farmers reduce agrochemical use by up to 60%. Available from: https://niqorobotics.com/products/robo-spray/.
51. Agri-EVE-EVE Corporate (2017) The new farm electric vehicles standard since 2017. Available from: https://www.agri-eve.com/.
52. Merlo (2024) A Enovitis in Campo il Cingo a guida autonoma Merlo pronto a stupire. Available from: https://www.merlo.com/ita/it/news-events/a-enovitis-in-campo-il-cingo-a-guida-autonoma-merlo-pronto-a-stupire/.
53. Cheng C, Fu J, Su H, et al. (2023) Recent advancements in agriculture robots: Benefits and challenges. *Machines* 11: 48. https://doi.org/10.3390/machines11010048
54. Mail MF, Maja JM, Marshall M, et al. (2023) Agricultural harvesting robot concept design and system components: A review. *AgriEngineering* 5: 777–800. https://doi.org/10.3390/agriengineering5020048
55. Bulanon DM, Burr C, DeVlieg M, et al. (2021) Development of a visual servo system for robotic fruit harvesting. *AgriEngineering* 3: 840–852. https://doi.org/10.3390/agriengineering3040053
56. Jia W, Zhang Y, Lian J, et al. (2020) Apple harvesting robot under information technology: A review. *Int J Adv Robotic Syst* 2020: 1–16. https://doi.org/10.1177/1729881420925310
57. Yeshmukhametov A, Koganezawa K, Yamamoto Y, et al. (2022) Development of continuum robot arm and gripper for harvesting cherry tomatoes. *Appl Sci* 12: 6922. https://doi.org/10.3390/app12146922
58. Wang Z, Hirai S, Kawamura S (2022) Challenges and opportunities in robotic food handling: A review. *Front Robot AI* 8: 789107. https://doi.org/10.3389/frobt.2021.789107
59. Zhou Z, Zahid U, Majeed Y, et al. (2023) Advancement in artificial intelligence for on-farm fruit sorting and transportation. *Front Plant Sci* 14: 1082860. https://doi.org/10.3389/fpls.2023.1082860
60. Xiong Y, Ge Y, Grimstad L, et al. (2020) An autonomous strawberry-harvesting robot: Design, development, integration, and field evaluation. *J Field Robot* 37: 202–224. https://doi.org/10.1002/rob.21889
61. Galloway KC, Becker KP, Phillips B, et al. (2016) Soft robotic grippers for biological sampling on deep reefs. *Soft Robot* 3: 23–33. https://doi.org/10.1089/soro.2015.0019
62. Fagiolini A, Trumic M, Jovanovic K (2020) An input observer-based stiffness estimation approach for flexible robot joints. *IEEE Robot Autom Lett* 5: 1843–1850. https://doi.org/10.1109/LRA.2020.2969952
63. Pedone S, Trumic M, Jovanovic K, et al. (2022) Robust and decoupled position and stiffness control for electrically-driven articulated soft robots. *IEEE Robot Autom Lett* 7: 9059–9066. https://doi.org/10.1109/LRA.2022.3188903
64. Dimeas F, Sako DV, Moulianitis VC, et al. (2015) Design and fuzzy control of a robotic gripper for efficient strawberry harvesting. *Robotica* 33: 1085–1098. https://doi.org/10.1017/S0263574714001155

65. Feng Q, Zou W, Fan P, et al. (2018) Design and test of robotic harvesting system for cherry tomato. *Int J Agric Biol Eng* 11: 96–100. https://doi.org/10.25165/j.ijabe.20181101.2853
66. Vrochidou E, Tsakalidou VN, Kalathas I, et al. (2022) An overview of end effectors in agricultural robotic harvesting systems. *Agriculture* 12: 1240. https://doi.org/10.3390/agriculture12081240
67. Four Growers (2023) Meet the GR-100 Tomato Harvesting Automation in Commercial Greenhouses. Available from: https://fourgrowers.com/products/robotic-harvesting-technology/.
68. Autopickr (2025) Gus-Asparagus harvester. Available from: https://www.autopickr.com/gus.
69. CREA (2024) Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria. News 23 feb 2024-Agrirobot, il robot per la raccolta della frutta, in campo. Available from: https://www.crea.gov.it/web/ingegneria-e-trasformazioni-agroalimentari/-/agrirobot-in-campo.
70. Tevel (2025) Our Technology. Available from: https://www.tevel-tech.com/technology/.
71. Agro Web System (2021) Artificial Intelligence In Agriculture. Agricultural rover—AutoProbe soil sampling system. Available from: https://agrowebsystem.com/en/autoprobe-soil-sampling-system/.
72. Black Shire (2025) Il robot-Robot RC 3075. Available from: https://black-shire.com/il-robot.
73. Field Robotics-Leading field-robot revolution (2025) Agriculture division. Available from: https://www.fieldrobotics.it/agricolture.html.
74. Vitibot (2022) Transizione 5.0 - Rispondere alle sfide della viticoltura sostenibile - Bakus. Available from: https://vitibot.fr/?lang=it.
75. AIgro (2025) Products—Aigro UP. Available from: https://www.aigro.nl/index_en.html#products.
76. Amazone (2025) Autonomous agricultural machinery, precision technologies and Controlled Row Farming. Available from: https://amazone.net/en/service-support/for-the-press/press-releases/latest/autonomous-agricultural-machinery-precision-technologies-and-controlled-row-farming-987748.
77. Sabi Agri (2025) Empowering agroecology with smart agricultural equipment. Available from: https://sabi-agri.com/en/.
78. Future Farming—Gateway to the world of smart farming (2024) Farmrobo iMog: autonomous multipurpose robot designed for small-scale farming operations. Available from: https://www.futurefarming.com/tech-in-focus/autonomous-semi-autosteering-systems/farmrobo-imog-autonomous-multipurpose-robot-designed-for-small-scale-farming-operations/.
79. Jin T, Han X (2024) Robotic arms in precision agriculture: A comprehensive review of the technologies, applications, challenges, and future prospects. *Comput Electron Agric* 221: 108938. https://doi.org/10.1016/j.compag.2024.108938