Robotics & Mobile Apps in Agriculture

Chapter 5: Robotics and Mobile Apps in Agriculture

Introduction

With the advancement of electronics, mechanics, and data technologies, the importance of integrating these technologies into robotics applications emerges. Thinking about benefiting from robots in agriculture began early (230). However, robots were not easy to integrate into agricultural and field operations, mainly due to their large size, high cost, and low return at that time. However, the development of artificial intelligence techniques made these robots do things that no one would have imagined that a machine would do. Nevertheless, robots outperformed humans in accuracy and speed.

Robots are programmable machines that replace human effort by doing complex series of actions accurately and fast (231). Unlike what we used to know about robots that they are human-like giants, robots might be just a robotic arm, an automated guided vehicle (AGV), autonomous mobile robots (AMR), or any other form that will be described later in this chapter. Robotic arms are used for welding, picking, handling, or packaging. Moreover, AGVs are used for delivery, moving tillage, or other applications. AMRs can manage warehouses, apply pesticides and fertilizers, and perform fruit picking.

Unlike robots that are standalone programmable devices, smartphone applications are just software programs installed on smartphones that convert them to powerful tools with some robotic functions.

In this chapter, we will discuss robotic techniques in agriculture in section 2, whether in the open-field or greenhouses, before and after harvest, with both plants and farm animals. In section 3, we will discuss mobile applications and their uses in agriculture.

Robotics in the agriculture sector

Robotic applications of field agriculture involve cultivation robots, plant protection robots (weeds, insects, and disease detection and removal), crop care robots (health monitoring, fertilization, and irrigation), and harvesting robots (232).

Tillage robotic applications

Plants need the soil to get nutrients, water, and air from within soil particles. After a cultivation season, the soil becomes compacted and full of plants residues. Soil compaction makes the soil less able to hold water and air that are essential for plant growth; thus, we need to perform tillage. Tillage is performed in two stages; primary and secondary. The primary tillage is deeper, needs more power, and leaves a coarse soil surface. On the other hand, the secondary tillage requires less power, produces finer soil suitable for cultivation, and shallower to refine the soil particles, kill weeds, and aerate the soil.

Robotic tractors are used for secondary tillage or easy tasks of primary tillage, i.e., if the soil is not too compacted. One of the unmanned tractors is the AgXeed robot, which is powerful to mount CAT III machines at the rear, and CAT II at the front. The robot is programmed through a graphical user interface showing maps of the field. Through the map, the user can define the area to be tilled, specify the start and end points, then send the instructions wirelessly to the robot, which can be activated and managed through a wireless remote control, as shown in Figure 36. Like most agricultural robots, AgXeed is equipped with cameras, GPS, 3D obstacle detection, and many other tools to ensure flawless unmanned operation.

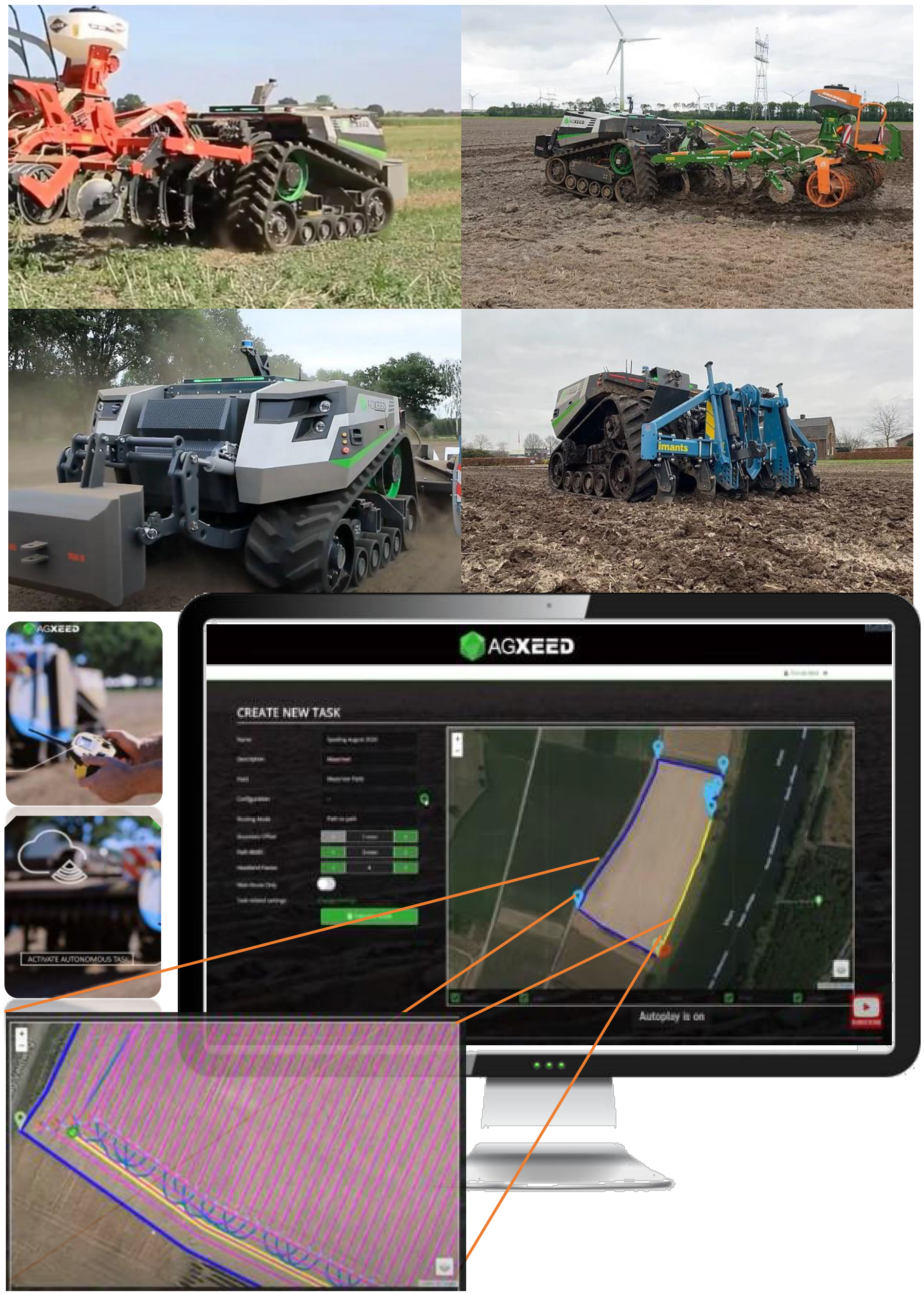

Figure 36. AgXeed robot while performing primary and secondary tillage tasks.

Planting robots

The following agricultural operation is sowing, seeding, or planting. Planters must place seeds or seedlings precisely at the desired distances from each other. Robotic planters help perform this task effortlessly. Figure 37 shows different commercial models of agricultural robots doing sowing tasks (Photos from DuckSize.com). Some of the shown models are specialized in planting, like Raven/DOT, Horsch/18M, and Agrointelli/Robotti, while others have some other tasks like weeding. Studies showed that such robots reduce operation time and costs compared to conventional planters (233).

Figure 37. Various types of robotic planters/sowing robots.(Pictures from ducksize.com)

Weeding robotic applications

After sowing, the plant needs several operations like weeding, irrigation, fertilization, and plant protection spraying and dusting

Weeding is the most frequent operation needed throughout the crop lifespan. Weeds have an adverse effect on crops as they compete for light, space, soil nutrients and water. They also host insects and other pathogens causing diseases to the crop. In brief, they reduce crop yield quantity and quality. To remove the weeds effectively, this should be done while they are shallow-rooted, small plants. However, they quickly sprout again leading to the need for repetitive removal of them. Removing the weeds is a tedious operation because it needs super attention while removing the weeds not to hurt the grown crop which is very near to the weeds. Recently, with the developments of computer vision with

AI, many Agri-robots are equipped with AI-driven cameras (like Farming Revolution and FarmWise products shown in Figure 38) that specify the exact location of the weed, then remove it without hurting the plant.

Figure 38. Some weeding robots. (Pictures from ducksize.com)

Plant protection robotics

To complete the plant protection loop, insects and diseases must be sprayed periodically. Despite its importance, applying pesticides has its side effects, as it harms the crop and may leave some residues that affect the final consumer as well. Conventionally, when we notice an insect infection or a specific disease, we apply the insecticide or the pesticide fieldwide because we could not differentiate between infected and healthy plants This application costs a lot of money and effort. With the AI-driven robots, the agro-bot can specify the infection zone precisely, and then it applies the appropriate amount of pesticide to this zone only. At the same time, healthy plants remain unsprayed, which saves time, money, and keeps the crops healthier to consume.

Similarly, when we notice that a crop spot lacks potassium or other nutrients that can be applied by spraying, the robot can specify the affected spot and apply the desired fertilizer directly to it without doing the same to the whole field. Figure 39 shows some robotic sprayers in action. Each one of them uses different technology and design of spraying.

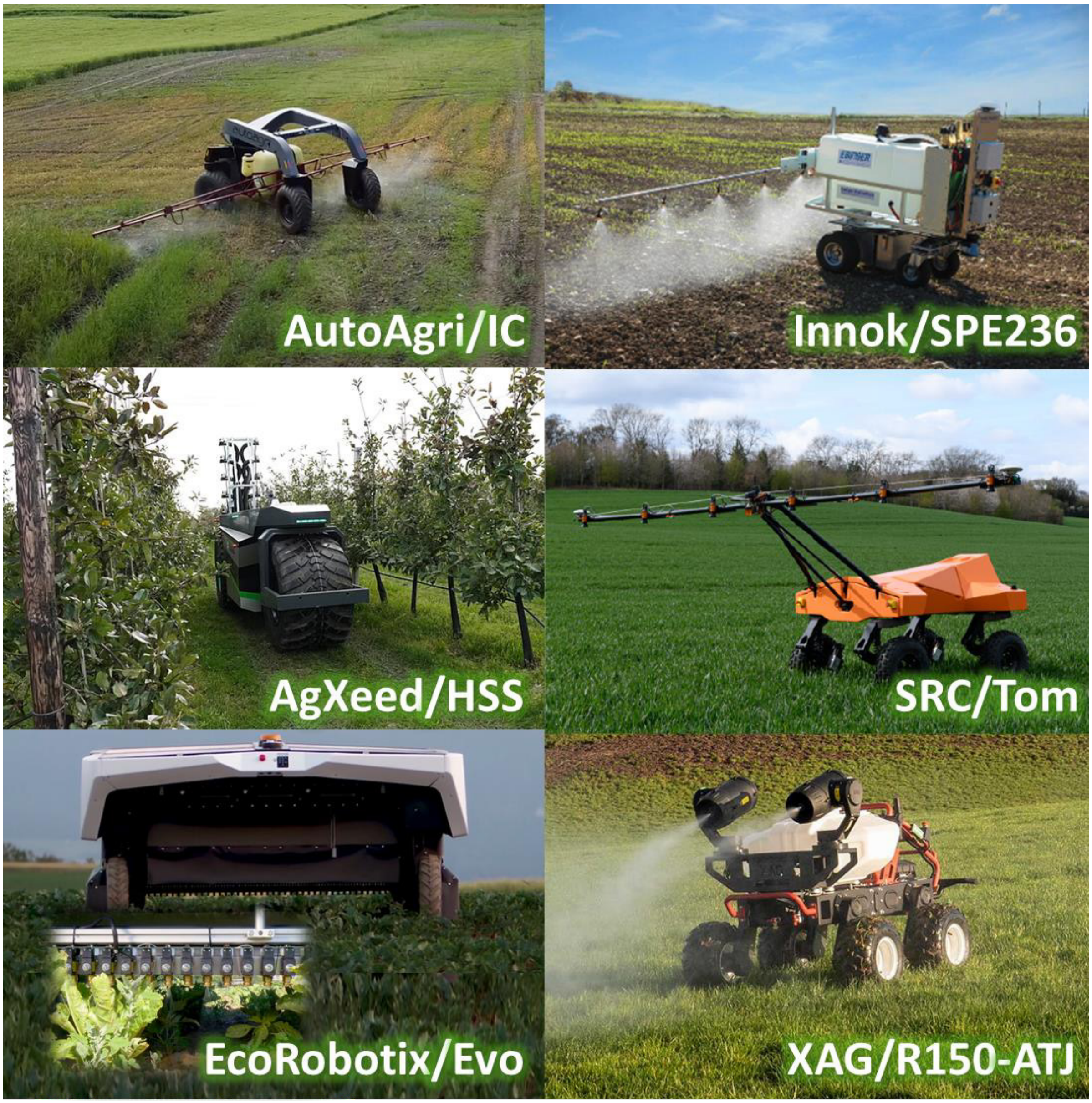

Figure 39. Spraying robots in action (various sources)

Robotic irrigation assistants

Unlike the robotic sprayers that always have an attached tank that holds the chemical being sprayed, irrigation robots rarely have one because of the large volume of water needed for irrigation. Instead, many of the robotic irrigators have an attached hose. Starting from lawn irrigators, Figure 40 a, b, e, they are robots that can be programmed to move automatically through the lawn while applying water as programmed. These robots have location and collision sensors and wireless connectivity that allow receiving orders and sending data about the situation of the grass if so equipped.

Figure 40. Different concepts of irrigation robotics

While these robots are moving, some other robots are fixed or move manually, Figure 40 f, g. These robotic sprinklers are equipped with advanced sensors to perform a specific function. The first one,

Figure 40 f, is a robotic sprinkler from InteliRain company. The sprinkler senses the direction and speed of the wind; thus, it adjusts the application intensity to reduce water flow if the sprinkling direction is by the wind direction, so it does not waste water for unnecessary overlapping due to wind. The inventors of this robotic sprinkler say that it reduces 30% of irrigation water (234).

The manual move robotic sprinkler, Figure 40 g, has a different concept. It is a programmable robot to adjust the angle and the intensity of the throw to aim to different plants to irrigate them while it is in the same place. For supplementary irrigation, there is a Plant Irrigation Water Sprinkler Agriculture Robot that is sold as a build-it-yourself kit (235), Figure 40d$_{1\&2}$. The robot comprises a moving base, water tanks, and a sprinkler, which is used for supplementary irrigation for trees. The problem with this robot is its small water tank. With a similar concept, the multi-function irrigation robot Aquarius is equipped with a large water tank used to deliver water to pots, Figure 40j$_{1\&2}$.

For greenhouses, the robotic arm Figure 40c is connected to a hose while it moves in a greenhouse. It is equipped with a camera and sensors to see the plant conditions, then applies the required amount of water as calculated by the controlling computer. For a larger scale, the hanging robot Figure 40i is designed to release variable application rates depending on the feedback from soil moisture sensors and the weather variables after calculating the desired water requirements of the crop. This system is called CASCADE, which saves 7% of the irrigation water (236).

The hardest part is to deal with large-scale cultivation, i.e., open fields irrigated using a center-pivot system. A recent innovation introduced a smart robotic add-on to the conventional pivot system, Figure 40h. the developed system adds cameras and other sensors to the pivot towers. The images are analyzed by AI computer to detect problems in the growing plant such as diseases, insects, and weeds (237). Additionally, the NIR cameras can detect the thirst degree of the plant to recommend increasing or decreasing the water application rate. Besides, the new system can detect any problem with the center-pivot itself, such as mechanical malfunction or nozzle clogging.

Harvesting robots

Mechanized harvesting of crops has developed a lot in the last decades. The engineering efforts lead to machines that combine several harvesting operations for many field crops. For example, the wheat combine harvester merges reaping, threshing, gathering, and winnowing. On the other hand, the sugar beets harvester combines lifting, cleaning, and separation. All these field crops have a uniform maturity date, and therefore, the whole field is harvested at once.

The problem is with the crops that ripen at different times, such as strawberries, tomatoes, and fruits such as apples. If we wait to harvest all at one time, the fruits that ripened early will spoil before they are harvested, and if we harvest them all early, we will get a large amount of the immature crop; thus, there will be significant losses. The practical solution is to continue harvesting daily, where the ripe fruits are collected first. Thus, the crops need a continuous harvest for a long time span. The problem with this matter is the need for a heavy workforce trained to work, which is challenging to obtain year after year, and if it is found, it is costly and not sustainable.

The robotic fruit pickers solved this problem through selective harvesting, which applies to greenhouses, orchards, and open fields (238). The modern robotic harvesters are equipped with vision sensors that detect the ripened fruit, a robotic arm that can pick the desired fruit precisely, and a mobile platform to pack the picked fruits and move them to the suitable warehouse.

Let us start with the crop that attracts the most interest to robotics makers, apple. The machine-aided harvest of apples has gone a long way in popularity among farmers and agricultural machinery companies. Many companies have designed giant combine harvesters that need workers to operate them. The workers drive the machine and direct the harvesting arms to the ripening apples that the worker selects with his expertise. Despite the success of these machines, they are labor-intensive and require trained laborers, which is the problem we talked about previously.

Many companies around the world have raced to manufacture robots to collect apples. That is why we find that the technologies in these robots are considerably different. However, it might be a positive difference. Each designer is keen to meet the farming conditions and the needs of farmers in his region. So, the resulting robot is as close to the human hand in its keenness to pick up the fruits without destroying them. Additionally, the robots use advanced computer vision and machine learning techniques to find the ripe fruits (maybe better than humans) and then pick them and deposit them gently in their bin.

One of the attractive designs of the picking arm is the suction arm picking. The robot moves through the crop lines taking pictures of the surrounding trees; then, it specifies the locations of ripened apples and then picks them with the suction arm. This robot is made by Abundant Robotics (239), Figure 41.

Figure 41. Suction harvesting robots of apples.

Unlike this single-arm picker, Figure 42 shows a multi-arm design that is more productive. The figure shows that this model from FFRobotics (240) has six independent arms on each side; each arm has a hand-like picker driven by the computer. The figure shows a single arm and two arms in action. The picking arm lands the picked apple on a conveyor that moves the fruit gently to the storage bins.

Figure 42. Multiple-arm apples' harvesting robot.

For tomatoes, robots have different designs as well. Figure 43 shows a robot that can harvest the whole tomato clusters, while Figure 44 shows another design that picks the fruits one by one. The robot in Figure 43 is from MetoMotion (241). They say that this robot harvests tomato clusters and performs other greenhouse operations for the crop like pruning, monitoring, pollination, and de-leafing. The robot's arm ends in a rhombus-like connected rod that expands to get around the cluster, then contracts to cut and handle it.

On the other hand, the single fruit harvesting robot, Virgo, from Root AI robotics company (242). This robot's arm is equipped with a three-finger picker that can precisely pick each fruit, and then it makes a 360-degree revolution to cut the fruit, then the arm retracts to place it in one of the attached bins, Figure 44.

Figure 43. Cherry tomatoes harvesting robots

The following important crop is strawberry. Strawberry fruits are susceptible to mechanical Injury, so the harvest and packing should be as gentle as possible (243). Strawberry is cultivated in greenhouses and open fields. Designers have developed a robot for each domain.

Figure 45 shows two strawberry harvesting robots, the first one (Figure 45a) is AGROBOT Robotic Strawberry Harvester designed to work in open fields and greenhouses (244). The robot has 24 independently operated arms that use real-time artificial intelligence and computer vision techniques to determine the ripen fruits using short-range integrated color and infrared depth sensors to capture other fruit properties. The arm grips the fruit from its stem to protect I from mechanical damage.

Figure 44. One-by-one tomato picking robot

The second robot (Figure 45b) is an open field strawberry harvester from Harvest CROO Robotics (245). The robot performs the picking, grading, and packaging of the fruits fully autonomous. The robot has 16 independent picking arms; each arm has several claws targeted by the computer AI to pick the ripened, healthy fruit. The claws are designed to surround the strawberry gently, then cut the stem to move it to the packing area. The robot is equipped with a 360 degrees camera that can grade the fruit size, color, and quality, to detect whether to pack it for fresh market or send it to processing within 15 milliseconds. Bell peppers are different from apples, tomatoes, and strawberries. The main difference is that its stem is too thick, so it is impossible to pick the fruit like apples or tomatoes; it needs to be cut to release the fruit. The first robot is SWEEPER, the product of a joint project between three universities and three corporations, funded by the European Union's Horizon 2020 research and innovation program (246,247). The robot uses computer vision to identify the location of the fruit, Figure 46a. It places a six-finger handle below the fruit, and a reciprocating cutter cuts its stem, then drops it in the collection bin. The average picking time of one fruit is about 24s, and the manufacturers said it could work for 20 hours per day. Thus it can harvest about 3000 fruits a day (247).

Figure 45. Strawberry harvesting robots

Another concept of harvesting the sweet pepper is introduced by the Harvey robot, a project funded by the Queensland Department of Agriculture and Fisheries (248,249). Harvey depends on advanced computer vision that guides a suction plunger to catch the fruit, Figure 46b, then cuts the stem and then releases the fruit gently in the collection bin. The project team said that they aim to expand the scope of the robot to harvest mangoes and other fruits. The third gripping method shown in Figure 46c is the robotic arm with a grip called the Fin-Ray gripper, which features a combined grip and cut mechanism This robot is one of the outcomes of the EU project CROPS, Clever Robots for Crops (250).

Figure 46. Bell pepper harvesting robots

Figure 47. Cucumber harvesting robots

Like the sweet pepper, cucumber has a hard stem that is needed to be cut to pick the fruit. The cucumber harvester, Figure 47a, designed for greenhouses by Wageningen UR, was one of the earliest robotic applications in agriculture in 2001 (251–253). The robot was slow compared to modern robots with computer vision advances. Many faster robots appear later, like the Root AI robot in Figure 47b (254).

In addition to the mentioned robotic pickers, there are harvesting robots for other crops, Figure 48, some of them are still in the early development stages, but they are promising for a better future in harvesting crops. Each of these robots is different in design to fit the physical properties of the crop. The asparagus robot, Figure 48a, handles the sprout and then cuts it at the bottom. The lettuce robot, Figure 48b, determines the target fruit, then picks the head while omitting the thick leaves (255). The grapes robot picker, Figure 48c, identifies the mature cluster, then carefully grabs its root, cuts it, and then moves it to the collection tray.

As for the citrus harvesting robot, Figure 48$e_{1,2}$, we find it works differently, as it determines the ripened fruits and then throws a cutting arm (like the concept of chameleon's tongue). The fruit is cut off, leaving it to fall to the ground, and then another machine comes to collect it (256). This method is faster in picking the fruits because it saves the time of putting the fruits in the collection box, but it may work for citruses, but it is not suitable for sensitive fruits such as grapes and apples.

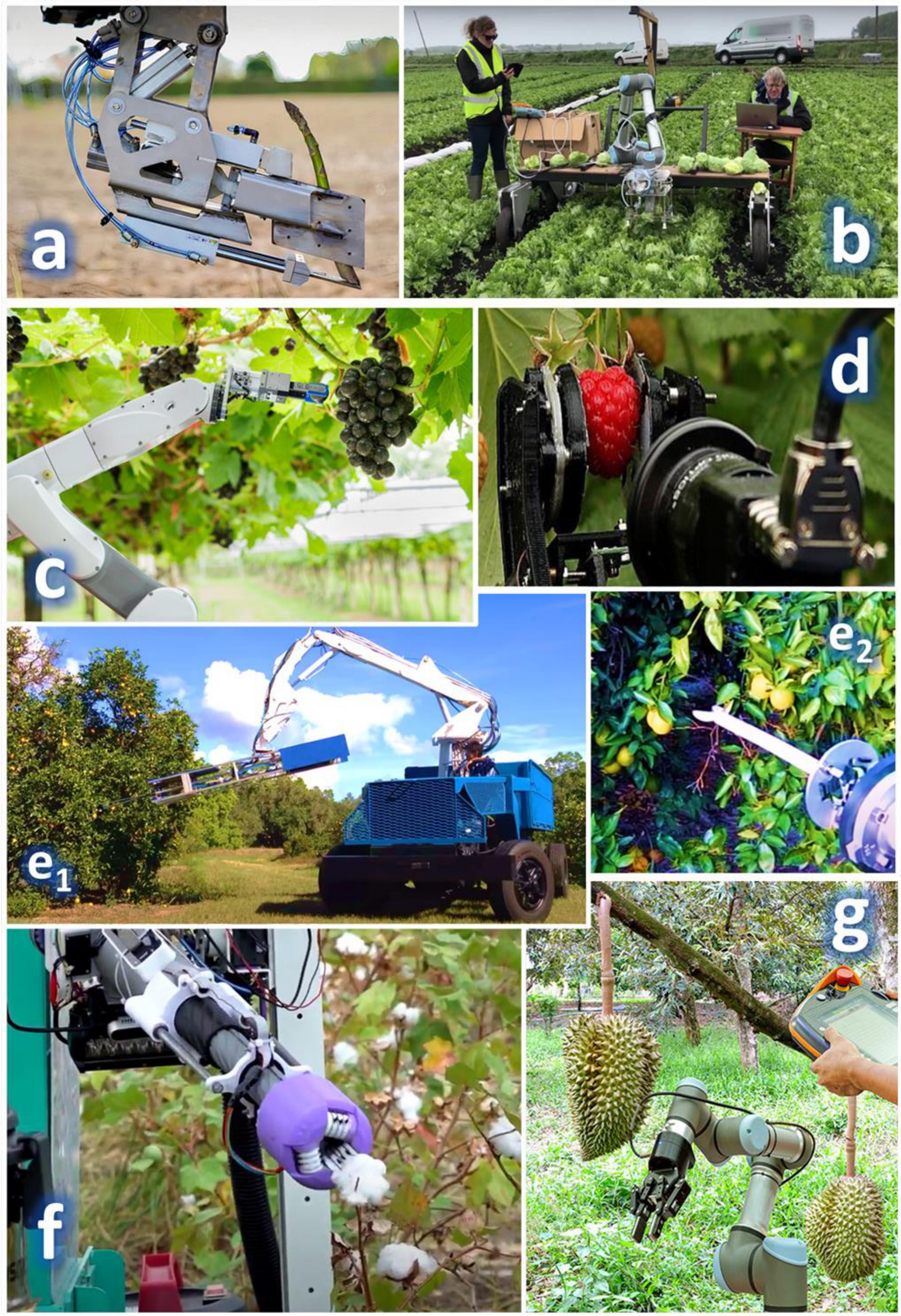

Figure 48. harvesting robots of miscellaneous crops

One of the less valuable robots is the cotton picker robot, Figure 48f, despite its high precision. The robotic arm can pick the cotton in an immaculate condition (free of impurities); compared to the mechanical combine harvester. However, the picking speed and productivity are not comparable to the mechanical harvester (257). In general, this robotic harvester is a good trial that might be developed to work faster to compete with the mechanical combine harvester or to be merged with the latter to get a cleaner product.

Finally, there are many other fruits that scientists try to automate their harvest to eliminate labor costs and increase the crop quality like Durian, Figure 48g, (which has a great taste with an unpleasant smell) and requires fast transport to markets. Although the science of agricultural robotics is still in its infancy, it has succeeded in establishing itself among farmers, pushing for more scientific research and funding for robotic development projects that increase food availability and reduce wastes to provide sustainable nutrition for humanity.

Livestock robotics

Robots in livestock farms have different roles Some of them work inside the barn and some work in the meadows. The first robots' group is the feeding robots, Figure 49a & b. The feeding robots are machines that take raw fodder, then they cut, weigh, mix, dose, and push feed up into place along the mangers. Some of these operations are optional, depending on the model. The robotic feeding systems eliminate the energy costs and prices of several separate machines for each operation eliminating labor to push the fodder (258). In the figure, we show two robotic feeders with similar functions, the Triomatic WB battery-powered robot from Trioliet company, Figure 49a, and the ARANOM feeding robot from HETWIN Automation Systems (259,260). To increase the feeding efficiency, we use the robotic feed pushers, Figure 49c & d. They are self-propelled, work 24/7 to push the fodder towards the animals so that they save labor costs, reduce fodder waste, and increase the feeding efficiency of the farm (258,261).

To maintain a healthy environment, the barn waste should be cleaned. Cleaning involves getting rid of manure and fodder litter. On most farms, there are several machinery types to do so, either mounted to tractors or chains. Robotic cleaners perform the task perfectly. They are of two types, robotic scrappers, Figure 49e, which scrapes the manure by a metal blade, and the robotic brushes (and scrappers), Figure 49f for cleaning fodder waste, and other finer cleanings (262,263).

For open fields, herding robots are doing more than just a herding dog. The herding robot SHRIMP, f14g, can monitor the cattle in the open field; it takes pictures of the animals, analysis the pictures with the readings of thermal sensors to determine the cow's health. Additionally, the pasture quality is being monitored by identifying its color, shape, and texture by AI analysis. Additionally, the robot can herd up to 150 cows forcing them to go to specific pasture areas or return to their shed (264,265). Another design of the farm assistant robots in Figure 49h is a robot called SwagBot. The robot can herd cattle, monitor them, and monitor plants. Additionally, it can be used on the farm to tow equipment and guide aerial vehicles (266,267).

Finally, there are many other robotics applications in the livestock field, like the rail-mounted straw blowing robots, Figure 49j, that prepare the cows' bed to ensure the best possible hygiene due to dry fresh bedding leading to improved animal welfare (268). Additionally, the milking robots, Figure 49i, provide better productivity than human-guided milking systems. However, the robotic system has a very high initial cost; thus, it is less profitable than the conventional milking systems (269).

Figure 49. Sample livestock robotics

Poultry robotics

The poultry industry is sensitive. A healthy environment is vital to keep the flock alive. However, some activities require intensive labor like collecting eggs from the floor, monitoring chicken health, and picking dead hens. Robotics have solved these problems and more(270).

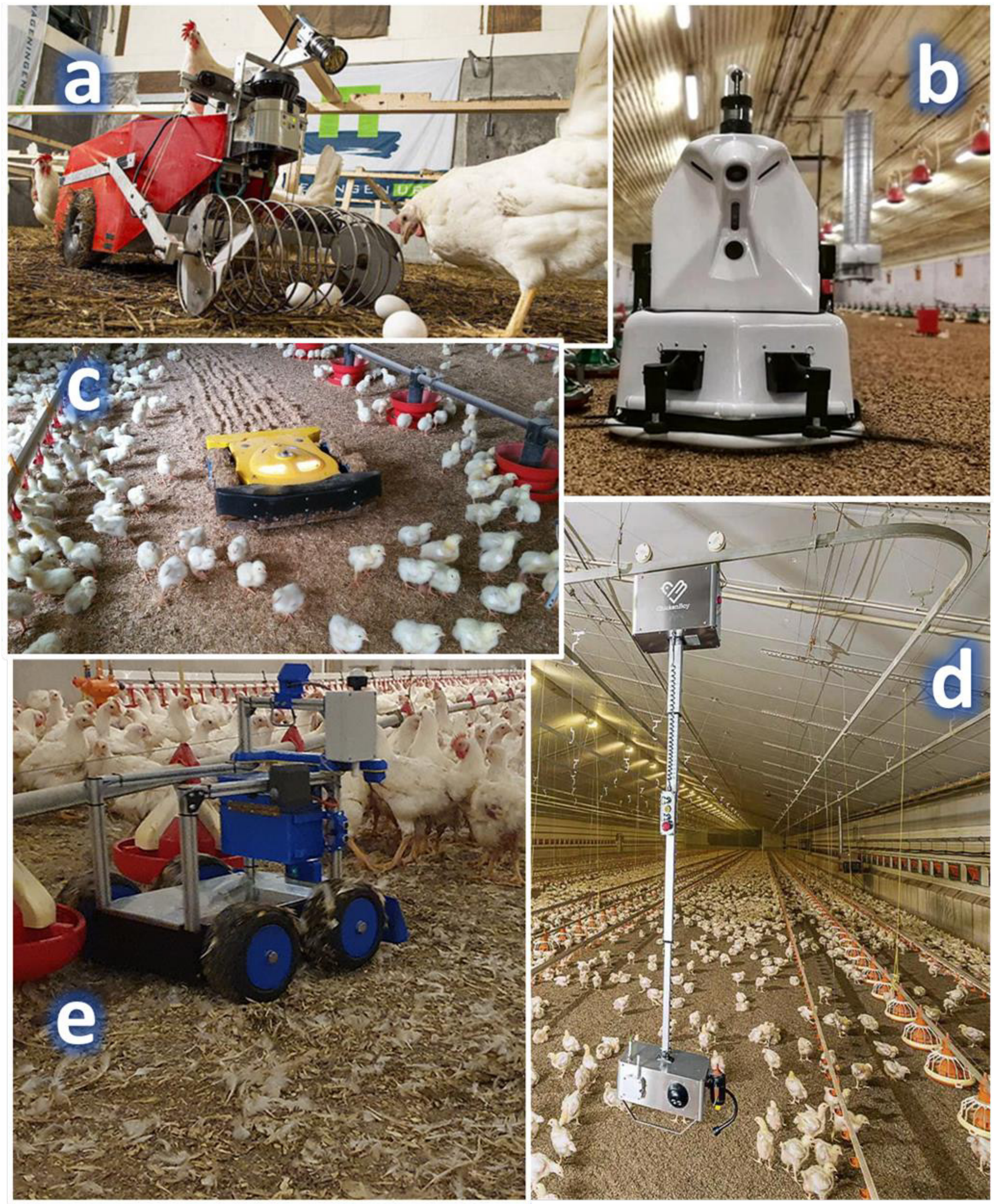

Figure 50. Robotics in the poultry industry

Figure 50a shows the PoultryBot robot from Wageningen University that collects floor eggs, monitors hens' health, and measure the environmental conditions of the barn(271,272). Another robot for keeping the barn environment healthy is the Octopus-Poultry-Safe robot, Figure 50b, later named XO robot (273,274). The robot marches through the barn while doing several tasks. The tasks include monitoring the chicken, measuring the environmental properties, detecting unstable conditions, and spraying disinfectants to ensure animal welfare and protect disease spread. The problem of which this robot is designed to solve is litter consolidation. The litter hardens due to the chickens' excretions, forming a severe bacteria base. The robot ventilates the litter and inhibits the fermentation process in soil and reduces the level of ammonia in the barns dramatically, which increases animal welfare.

To monitor and enhance the environment of the chicken barn, the ChickenBoy robot, Figure 50d, supports the monitoring tasks of the broiler. The robot is hung to a curved connected tray at the ceiling (No contact with the hens). It scans every part of the barn while moving. The robot monitors and reports defective drinkers, leakages, and wet spots, in addition to birds' health (by motion detection and excrements rating to detect intestinal diseases). Additionally, it continuously measures temperature, relative humidity, CO2 emissions, ammonia concentration, airspeed, noise level, and light intensity (275,276). The Iamus robot, Figure 50e, measures similar environmental properties while moving on the floor, allowing it to monitor individual birds' vitals (277–279).

Finally, we have The Spoutnic chicken robot, Figure 50c, which moves through the barn like a fox. This continuous motion prohibits the chicken from laying eggs on the floor; instead, they lay eggs in the desired boxes. Additionally, the robot's movement keeps the hens more active, healthy, and productive. The robot can be equipped with tools to aerate the litter, keeping it healthy and avoiding bacteria and undesired gasses contamination (280–282).

Miscellaneous robotics in agriculture

In addition to the function robotics mentioned before, some unique robots helped solve particular problems. Figure 51a shows The Grain Weevil robot by JLI Robotics (283,284). This robot solved an old problem of grain bins. We know that the grain silos are unloaded from the bottom. The adhesion between grains causes the upper layers to consolidate. This consolidation stops the flow of the grains. To solve this problem, the farmers enter the silo to move the piled grain to aerate it and push it into the exit hatches. However, several problems occurred due to the suffocating atmosphere inside the silo, which causes respiratory diseases, most notably what is known as the Farmer's Lung. The biggest problem is that the farmer may fall because of his weight in the empty areas, then the crops will fall on him, which leads to suffocation and death. The idea of this robot is that it does everything the farmer used to do by moving, un-piling, ventilating the grains, and pushing them to the exit holes. At the same time, it can get out from under the grains if they fall and continue to work in the bin.

The second category is the greenhouses robots, Figure 51b, which can inspect the plants like an expert, moves them from slot to slot, applies some chemicals, and do other activities that we discussed before. The next category is in nurseries, where pots must be moved frequently for ventilation, solarization, or other organizational purposes. This operation requires much labor, and it can be solved by a set of robots, Figure 51d. Although the function of this robot was not easy for humans, causing back pain, it is easy for a robot to do it more frequently and under any weather conditions.

The fourth robot is the Bug Vacuum robot from AgRobot, Figure 51c, which is a self-propelled bug vacuum that can remove insects by sucking them into the vacuum containers, hence killing the bugs without the use of insecticides. Either to avoid the hazards of the chemicals or because the bug is resisting the pesticides. The robot can navigate autonomously within the crop rows (285,286).

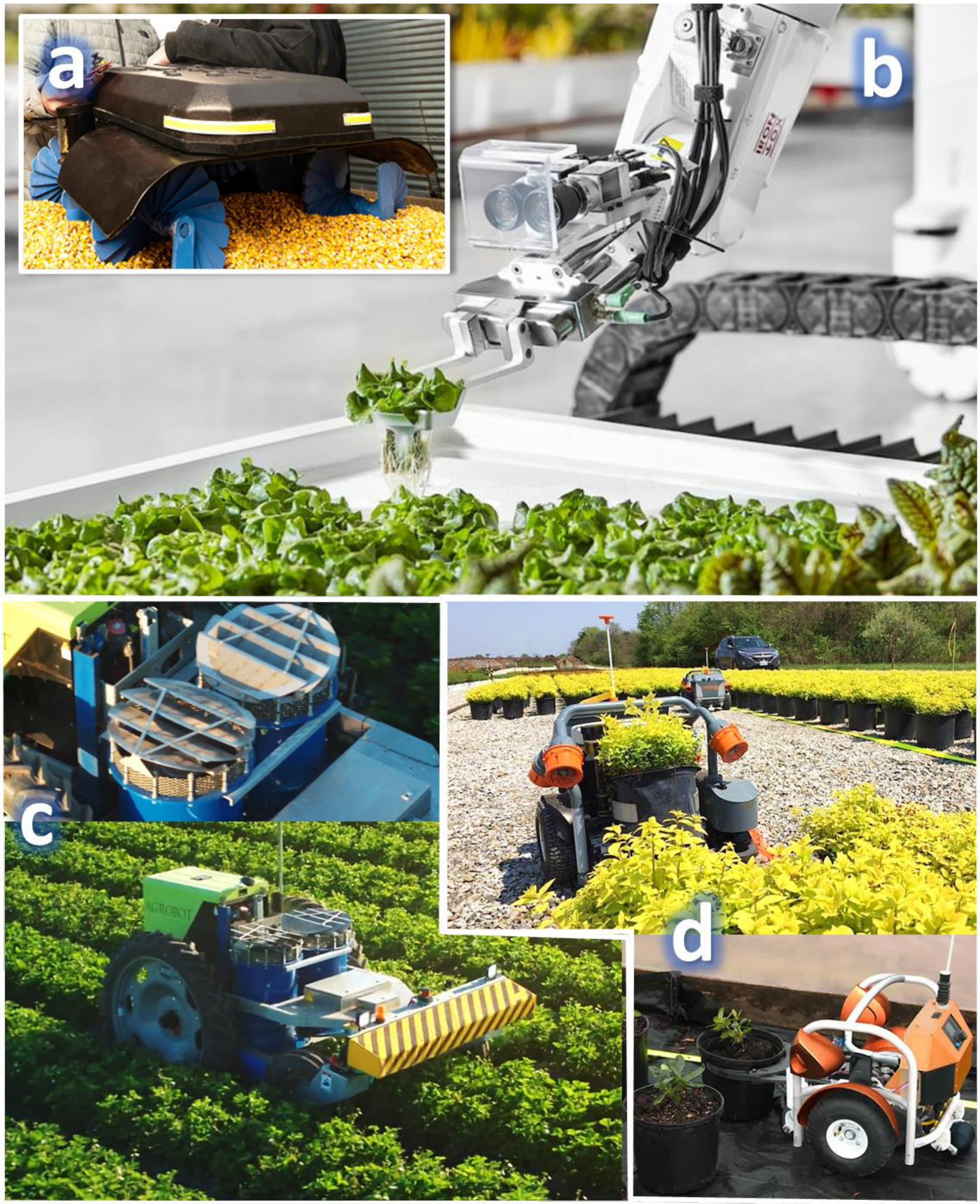

Figure 51. Other robots in agriculture

Figure 52. Exoskeletons robotsin agriculture

The last category of miscellaneous robotics is the exoskeletons robots, Figure 52. The exoskeletons are wearable mobile machines powered by electric motors, pneumatics, levers, hydraulics, or a combination of technologies that allow for limb movement with increased strength and endurance (287). These wearables can transfer farmers into superpowered robots who can lift heavy weights effortlessly, as in Figure 52a & c, where seniors and juniors carry heavy loads easily. The exoskeletons can help people do tedious jobs without hurting their bodies, Figure 52b.

One of the best applications of the exoskeletons is for laborers whose work requires raising their hands for a long time, Figure 52e & f. This case applies to greenhouse technicians and field workers working in pruning, de-leafing, and harvesting. These robotic exoskeletons avoid the severe muscle aches caused by such types of work, as they can support the hands to do work effortlessly whatever the time it takes (288–291).

Smartphones' applications

Smartphones are now everywhere. Whether in the developed world or developing countries, whether in urban or rural areas. Even a person's economic situation does not hinder him from owning a smartphone. These phones have become accessible to everyone, despite the varying specifications and capabilities. However, they all have a camera, GPS, the ability to access the Internet, and they allow the installation of various applications.

Smartphones came with different operating systems (OSs). The primary OS types are Android OS from Google and iOS from Apple. Both systems contribute about 99% of the market share (69.71% and 29.51% respectively), other OSs that take less than 1% of the market share (Stats of February 2022, Statcounter.com). Each OS has its applications' store, where the applications are not interchangeably compatible. This means that the developers must develop two separate versions of each application: one for android and the other for iOS. The decision of which OS has the priority depends on the target users. While Android is the dominant system globally, this is not the case in the North America and Oceania markets (about 40% and 60% for Android and iOS, respectively). At the same time, in developing countries like India, the share is 95% and 4%.

Smartphone apps have different functions. The functions can be categorized into the following:

- Informational apps
- Logistics and trading apps
- Diagnosis apps
- Monitoring and control apps
- Measurements and calculations apps
- Farm management apps.

Figure 53 shows the spectrum of mobile applications, we will explain each category defining the types of applications under it.

However, since there are dozens of applications under each type, and because they vary according to the operating system and even according to the user's country, we chose not to mention the names of the applications and only mention their general specifications.

Figure 53. Agricultural mobile applications' specrum

Informational apps:

Informational apps are applications that provide useful information to the farmer. This category includes:

- weather apps that provide weather predictions and warnings, where farmers can take actions accordingly. Specific weather apps can provide information about soil moisture conditions and precipitation reports.
- News apps: They provide different information about farming environments and markets.
- Information apps: They provide information about soil types and properties at the user's location. This type of app also provides information about local plant types and species, as well as information about suitable livestock and poultry.
- Regulations apps: they contain farming-related regulations and rules generally associated with governmental agencies and farmers' unions.
- Catalog apps: this type is associated with producers of farm supplies, like fertilizers, machinery, seeds, irrigation supplies, and so on. These apps replaced the conventional paper catalogs to be cheaper, more accessible, and up to date.
- Forums apps: they provide access to peer farmers and experts that can provide solutions for farming problems either in real-time or in a short time. Many apps under this section cover many fields, like Cattle forums, poultry forums, and forums for some specific crops.
- Reference apps: under this type, some apps contain all information about some farming businesses. For example, some apps can provide all information about cattle, like their breeds, purpose of breeding, tips for best management, health, and other info. Similar apps exist for crops, bees, poultry, etc.
- Educational apps: the educational apps do not just provide information about some farming practices but provide instructions on how to do them effectively by providing step-by-step information, pictured tutorials, and videos

Logistics and trading apps

Logistics and trading apps help the farmers to manage their inventory, get their supplies on time, and to sell their products at a reasonable price. This category contains the following types of applications:

- Trading platform apps: these are like virtual markets, where the farmers can display their products and receive quotations. They can also purchase agricultural supplies after reviewing the prices and specifications of the various competitors. Apps under this type include virtual cattle market, where farmers can bid on their livestock.
- Logistics apps: in this type of app, farmers can keep track of the stock of fertilizers, pesticides, seeds, forage, fuel, and other farming supplies. These applications save stock status and alert farmers before they run out of items and may provide a way to order such products.

Renting apps: Through these apps, farmers can rent some equipment, tools, or machinery. Many of these apps are associated with rental companies.

Agricultural jobs apps: This type provides an easier way for farmers to search for laborers and for laborers to find jobs.

Accounting apps: These applications carry out the accounting tasks of the farms. The apps track costs and selling prices and calculate the profits after deducting costs, rents, and other fees. Some of these apps also calculate governmental taxes and prepare taxes forms. Other apps can calculate the appropriate selling price for each product.

Diagnosis apps:

Modern smartphones have powerful facilities to make complex computations and access databases. They are equipped with cameras and other sensors that can be used in diagnosing diseases and performing other tasks depending on cameras and AI apps. The diagnostic apps include the following:

Crops nutrients diagnosis: these apps can identify crop nutrient deficiencies through crop pictures (some apps may require answering some additional questions). Some apps can recommend applying some fertilizers and suggest the required dosage.

Crops disease diagnosis: like the previous type, this type can diagnose other diseases than infect the plant, either viral, bacterial, physiological, or caused by other pests. Some apps also suggest using some pesticides and providing the application quantity.

Insects' identification apps: these apps can identify different types of insects to order the proper insecticides.

Animals' diseases diagnosis: these apps are AI-trained to identify livestock and poultry diseases using the mobile camera. However, these apps are not a substitute for veterinarians.

Monitoring and Control apps:

This category includes the applications associated with other IoT hardware like monitoring cameras, gates, valves, and all controllable devices on the farm. These apps have the following types:

Farm monitoring apps: they are usually linked with cameras in the field and farm entities. Farmers can see their farms from anywhere. They can receive alerts of intruders and see their crop and livestock status. Accordingly, farmers can take action through such apps by closing the gates, opening/closing irrigation valves, or taking other actions like calling the veterinarian for a sick animal.

Control apps: IoT valves, devices, and gates can be controlled through different apps. Some devices can be controlled through the monitoring apps, while others require separate apps.

Zoning apps: through these apps, the farmers can specify the working area of the machinery through tillage, spraying, or harvesting. They can also specify a grazing zone for their livestock through e-fencing. The zoning apps are also used to specify the path of the drones.

Breed Management apps: these apps monitor individual livestock animals. They log their well-being factors through attached sensors and warn the farmer of any suspected problems. Some of the apps are associated with calving sensors that warn the farmer if the cow is about to calf.

Drone control apps: in addition to the zoning apps, most drones come with an integrated management app that can specify the drone's path and control its sensors like cameras, sprayers, and holders.

Measurements and calculation apps

Smartphones have powerful processors that can be used for complex calculations. Several farming applications require simple or complex calculations. The following types are included in this category:

Crops' calculation apps: these apps provide one or more of the following calculators:

- Growing Degree Days (GDD) calculator that measures the maturity of the crop based on the daily temperature difference through the growing season.
- The required amount of seeds of each crop
- The mixing sequence and ratios of pesticides
- Grain loss calculator
- Planters and sprayers adjustments calculators
- Fertilizers' calculators
- Irrigation scheduler
- Soil quality calculators

Livestock calculations apps: these apps provide one or more of the following calculators:

- Calculate the Expected progeny differences (EPD) values of cattle. (EPDs are predictions of the parent's genetic transmitting ability to its progeny. These values are used to select the herd's desired traits)
- Calculate the feed amount per head
- Calculate the herd's supplement intake and replacement date.
- Calculate calving and breeding dates.
- Calculate dosages for medications.
- Calculate animal performance measures.

Counting apps: these apps use AI to find patterns in pictures so that they can count the number of birds in a poultry barn, the number of wood logs in a pile, and even the number of pills or seeds if laid on a flat surface. These apps are beneficial and save much time; however, they might need some calibration to improve their results.

Management apps:

Farm management apps are a mix of all the apps mentioned above. However, some apps are designed to integrate all the above into one app. For example, some apps provide reporting and recordkeeping of all farm practices like the water and soil qualities, amount of applied irrigation, daily crop status, spraying logs, etc. For livestock farms, the app keeps logs of individual animals, the applied medications if any, the physiological measures of each animal, and so on. Additionally, the managing apps can track costs and profits and suggest methods to reduce costs and increase revenues. The management apps should manage tasks scheduling and provide essential information like weather, news, and prices variations.

Challenges and obstacles

Agricultural robots have conquered all agricultural fields, enhancing the performance of many agricultural operations and making them more accessible and precise. However, to complete the picture, we must cover the problems and challenges of robotics in agriculture. The challenges are divided into two parts, a technical section related to the manufacture of robots and a section concerned with the challenges of wide adoption of robots in the world in general and in developing countries in particular.

Technical challenges

Technical challenges include challenges regarding the crop and the farm, and other challenges regarding the robot design like sensor's efficiency and price, the safety of operation on the crop and the farm environment, robot multitasking, operating speed, robustness of the design and troubleshooting problems.

Farm and crop challenges

Although robots are intelligent machines, their intelligence is based on order and organization. The weeding robots are trained to know the shape of the crop and the shapes of weeds in the area; if some weeds are like the plant in shape, it will be hard for the robot to operate efficiently. The harvesting robots, however, expect the bushes to be vertical, and the fruits should be near and mostly exposed to the robot's cameras.

Thus, we should prepare the crop environment to make the robot's job more accessible and successful. For example, modifying the cultivation system of cucumber to be on a high-wire system, pruning and de leafing the plants, modifying the design of the mechanized milking system, and alternating the melon along the row (292). All these examples are adaptations of the existing systems to be compatible with robots.

Additionally, we should select suitable cultivars with properties that are easier for the robot to deal with them. For example, selecting cucumber with longer peduncle and bell-pepper with non-clustered positioning that is easier for robot's catchment and differentiating between ripen and non-ripen fruits. (292).

Sensors' efficiency vs. price trade-off

As for the sensors, the most used sensors in robots are image sensors, the accuracy of which varies greatly and is directly proportional to the price, which makes there a strict tradeoff between accuracy and price. Additionally, the use of sensors for a particular spectrum of light such as near-infrared (NIR), which are very useful in analyzing plant images, raises the price. We mentioned one category of sensors, and there are a lot in robots such as proximity, location, collision sensors and many more. Add the motors and actuators that drive the robotic arms, wheels, etc. Accurate and reliable types raise the price of the robot dramatically.

Operation safety

Robots are machines; they are designed to perform specific tasks. Each robot is equipped with the facilities that make it perform its job without hurting the plant, not causing any trouble to the farm enmities or workers (292). For example, the harvesting robots have cushioned handles to protect the fruits while picking, and they usually move the picked fruit softly to the bin to preserve its quality. The autonomous weeding robots were designed to kill only weeds while preserving the planted crop. Sophisticated machine learning algorithms differentiate between the crop and other weeds. Most moving robots are equipped with advanced collision protection sensors, like proximity sensors and computer-vision-based algorithms to avoid accidents.

Multitasking

Unlike humans, robots can only do what they are designed for it. Harvesting robots cannot weed the plants, and tillage robots cannot help in the livestock barn. However, some robots are designed to do several related tasks. For example, a robot monitors the livestock, herd them, and monitors the pasture's quality; and another robot in greenhouses, where it can harvest the fruits, deleaf the plants, and monitor diseases and pests. The human hand can be used for picking, handling, digging, pulling, and many more tasks. The human can be trained easily to perform any task on the farm, using any tool.

On the other hand, robots, until now, can only do the jobs they are designed for because their pickers are so specific to one or two tasks. Future developments may improve the robots' hands to be like the human hands and enable training the robots to perform tasks other than the design jobs. This dream might come true using the reinforcement learning algorithms that allow the robot to learn from its faults until it reaches perfection doing any job (293–295).

The workload is also an important factor especially for large farms. The design of the robot should differ in large farms than for small farms. For example, single-arm robots can be effective for greenhouses or small farms, while we need faster multi-armed robots for fruit picking for large farms. The sensors and hardware speeds should also vary for higher workloads. These changes, however, should not increase the robot price too much because the additional parts are not as expensive as the common parts (296). Using multifunctional robots can dramatically improve performance and reduce ownership costs (297). More information about multifunctional robots is in section 0.

Speed and robustness

Regarding the speed of operation of the robot, this challenge is improving with advances in hardware and artificial intelligence techniques. This point is one of the most prominent drawbacks to robots. Farmers always compare them to the efficiency and speed of the humans, and the manufacturers respond that the robot can work without rest or holidays and under any weather conditions, as well as many robots can work during the day and night. However, these advantages do not come smoothly. In fact, a robot, like any machine, can break down and need to be repaired, reprogrammed, reset and cooled from time to time, and its batteries need to be charged (298). Hence, it is essential to consider speed, ease of use, and low maintenance needs as factors that encourage farmers to acquire robots in their farms (296).

Imaging efficiency

Most robots rely on cameras to view their target and their surroundings. However, cameras take two-dimensional photos (2D), while the robot acts three-dimensional (3D). For example, the harvesting robots take pictures of the plants and the fruits, and then they identify the ripened fruit's location and size to send their claws to grab it. The 2D picture is not sufficient to determine the precise information, so the robots tend to take several photos from different angles to build the 3D network in memory, then specify the exact properties. Additionally, the agricultural environment is dynamic and has high variability. Thus, the visibility model should be well trained and subject to frequent evaluations to improve it if necessary.

Nevertheless, the illumination affects the accuracy of the pictures. Thus it should be taken into account while training the different illumination levels, whether the robot will operate in day or nights, natural or artificial light (299). The imaging efficiency issues also apply to all vision applications, like monitoring, herding, and diagnosis.

Challenges for wide adoption of robots

Robots can make farmers' life more accessible and their job more profitable. However, the wide adoption of robots is hindered by some obstacles. In the following sections, we will cover most of these obstacles.

Economics and Costs

Robots are expensive; initial and operating costs are high (298,300). To urge farmers to invest in robots, they must feel that the robotic systems will save them money. According to several investigators (296,300), saving money involves that the robots should:

- Increase the farm productivity in quantity and quality.
- Decrease variability and uncertainty of the production.
- Reduce labor costs.
- Protect laborers from injuries and harsh working conditions.

Reducing the costs of ownership can be done by several methods:

Using multifunctional robots can reduce costs of ownership. All robots have the main microprocessors, batteries, and sensors, but they differ in software, and some terminals, like the clipping arm of harvesting robots. In the future, it is expected that harvesting robots will have changeable arms to suit all picked fruits instead of one crop only. Hence, we can combine robots with near functions to be one robot with multi-tasks; for example, we expect to see a robot that can do tillage, weeding, planting, spraying, and monitoring, and another robot for de-leafing, harvesting, sorting and packing (297).

Governmental financial support can also reduce ownership costs. Governments can subsidize farmers to acquire robots by reducing taxes and customs duties, or by buying the robots and then renting them to the farms.

Laborers and social problems

Agriculture is a labor-intensive industry. Due to the usage of technology and machinery, more laborers are needed in developing countries than in developed countries (300). Losing jobs is one of the worst side-effects of using advanced technologies like robots. On the other hand, robotics can generate new jobs for maintenance and repair, training, and selling. However, robot's performance is still less than human performance, and they need human supervision in most cases. In many cases, we need collaboration between robots and humans in some fields like harvest, so that robots perform most of the harvest work, while humans complete the rest that is "still" hard for robots to do (292). The most acceptable part for robotics is when robots replace humans in hazardous operations like spraying pesticides or going into the grain silos, as discussed in sections 0 and 0.

Knowledgeable human resources

Robots need skilled professionals to design, operate, and maintain. Lack of a trained workforce is one of the problems limiting the widespread robotics in agriculture. To overcome this problem, we must investigate local staffing to add specialized educational programs in the universities and organize training programs for talented agricultural engineers and computer scientists to enter this field (298,301).

Standards and cooperation

While preparing this report, I found several pages that claim "the first robot in the world that harvest …" The surprising thing is that the publishing dates of each claim are years apart, not days! This confusion reflects the problem of lacking coordination between robot designers.

On some published success stories, I found evidence of a lack of coordination and cooperation. The designers said that a farmer came to them, explained their problem, and asked the robotic designer to solve it by inventing a robot, which they did for him. However, others are doing the same elsewhere without common standards that each designer should follow. This lack of coordination wastes time, effort, and money of the designers and makes the final product more expensive and less affordable.

If we have agricultural robotics standards, we will save time, effort, and money. This standardization process is discussed in some posts (302–304) by the Global Organization for Agricultural Robotics and other researchers. However, it is still under development and needs cooperation from worldwide.

Standardization should include the training and test conditions of the robot to cover the conditions worldwide, not only a specific farm. These conditions involve non-uniform soil surfaces, different textures, several illumination and weather conditions, and so on (297).

Legal issues

Although robots are helpful machines, they can be extremely dangerous if gone out of control. As an always-connected device, the robot can be hacked and reprogrammed to perform undesired actions. Additionally, they can disclose their data to undesired parites. This issue raises some questions; who is responsible for this? The owner, the operator, or the manufacturer? What if the robot had an accident? Who owns the data it generates? What if a robot destroys the crop, who will pay for that? What is the insurance companies' liability in such cases?

All these issues must be addressed and clarified by governments and policymakers to ensure the flawless spread of robots in the agriculture communities. More about the ethical and legal challenges of robots can be read at Ebers (305).