Smart Agricultural Technology 9 (2024) 100516

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Application of hyper-automation in farming – an analysis

Sairoel Amertet [a,*], Girma Gebresenbet [b], Hassan M. Alwan [a]

[a] High School of Automation and Robotics, Peter the Great Saint Petersburg Polytechnic University, Saint Petersburg 195220, Russia
[b] Department of Energy and Technology, Swedish University of Agricultural Sciences, P.O. Box 7032, Uppsala 750 07, Sweden

ARTICLE INFO

Keywords:
Hyper automation
Agriculture 4.0/5.0
Precision agriculture
Smart agriculture
Robot communication
Agriculture digital
Multirobot system
Agriculture mechanization

ABSTRACT

The purpose of agriculture is to support humankind. There are currently 7.7 billion people on the planet and this figure will increase to nine billion by 2050. As the population grows, even greater amounts of food will be needed, creating a significant challenge for farmers. Emerging digital technologies such as hyper-automation have the potential to revolutionize conventional agricultural methods. This study assessed the current use of hyper-automation systems in agriculture and examined whether new uses of this technology could benefit agricultural industries. One example could be to use an automated variable-seed control system, which has reported seeding accuracy of 98 %, indicating a cost-effective solution. Overall, our analysis revealed that to sustain future agricultural production and ensure food security, countries throughout the world need to focus on hyper-automation in the agriculture sector.

1. Introduction

Agriculture, one of the foundations of human civilization, has developed significantly over time. Increasing numbers of farmers worldwide are now turning to smart agriculture, which involves using cutting-edge technologies to improve crop yields, facilitate precision farming, and reduce resource use [1]. Hyper-automation, which integrates artificial intelligence and machine learning to automate repetitive processes, improve decision-making, and increase overall efficiency, is one of the most promising technologies for the industry. Hyper-automation can enable sustainable farming methods and transform smart agriculture [2].

According to the Fourth National Climate Assessment (NCA) of the U. S. Global Change Research Program, extreme weather events such as heat waves, droughts, wildfires, and flooding will have increasing impacts on agricultural productivity between now and 2050. Therefore, farmers will be unable to depend on traditional weather forecasts, making it challenging to plan ahead or even follow their regular planting schedule. Farmers in nations vulnerable to drought or other natural calamities will bear the brunt of inaccurate data.

Extreme weather events provide an ideal environment for pests and illnesses, which lower crop productivity [3,4]. Pests devastate crops in a variety of ways, e.g., by devouring leaves, sucking out liquids, spreading plant diseases, feasting on natural fibers, and burrowing into leaves, roots, and stems. Pest damage frequently has significant economic repercussions, while crop losses from diseases, weeds, and insects can be expensive and irreversible [5]. As a result, managing diseases in large-scale farming can be laborious and time-consuming and, in the absence of accurate data, infections can spread quickly and cause enormous crop losses. The difficulty in managing pests and diseases is compounded by the ideal conditions created by extreme weather for the development of microbes and diseases [6].

A comprehensive evaluation of this subject area is necessary to identify the main research gaps. This study examined how hyper-automation systems are being used in agriculture and evaluated whether new hyper-automation applications can be advantageous to the sector [7,8]. Several scientific databases were searched for pertinent papers for the analysis.

The remainder of this paper comprises: a literature review (Section 2), a description of methods (Section 3), results and discussion (Section 4), some conclusions (Section 5), and some limitations and opportunities of hyper-automation applications and recommendations (Section 6).

2. Literature review

Smart agriculture refers to the use of advanced technologies on farms, where the ultimate goal is to increase the quality and quantity of crops while optimizing human labor use (Fig. 1). Examples of technologies used in smart agriculture are [9]: precision irrigation, climate management, sensors, software platforms, location systems (GPS,

---

* Corresponding author.
E-mail addresses: sairoel@mtu.edu.et (S. Amertet), girma.gebresenbet@slu.se (G. Gebresenbet).

https://doi.org/10.1016/j.atech.2024.100516
Received 18 April 2024; Received in revised form 21 June 2024; Accepted 26 July 2024

satellite), communication systems, robots, and analytics and optimization platforms. All these are linked by the Internet of Things [10] providing connectivity between sensors and machines, resulting in a complex system that allows farmers to monitor processes on their farms and take strategic decisions remotely, from their tablet, phone, or other mobile device, rather than in the open field, greenhouse, orchard, or vineyard [11].

2.1. *Hyper-automation farming*

Emerging digital technologies have the potential to change traditional agricultural practices. The Food and Agriculture Organization of the United Nations describes this change as a “digital agricultural revolution”, which could help ensure agriculture meets the needs of the future global population [13]. Others call the change “hyper-automation and Agriculture 4.0/5.0″ [14], indicating a fourth/fifth major agricultural revolution, although the precise dates of these are unclear [15]. According to the World Economic Forum, hyper-automation and the fourth industrial revolution (which includes agriculture) will unfold throughout the 21st century, so perhaps the year 2000 or shortly thereafter marks their beginning. Agricultural revolutions over history have involved periods of technological transformation and increased farm productivity [16] (Fig. 2).

For thousands of years, people lived as hunters and gathers, until the invention of cropping systems shaped civilization in profound ways. However, the global population is now growing at a very fast pace [17] and demand for food is escalating, posing challenges to existing agricultural systems to increase production, but in a sustainable way in the long term. In a global movement giving reason for hope, new technologies can give higher crop yields while reducing environmental impacts.

Revolutionary agricultural technologies (hyper-automation) involve the use of e.g., sensors that monitor the condition of each single plant, systems that milk cows and check their health faster than any person could, and autonomous field robots that remove weeds mechanically [18].

Agriculture has a clear goal: sustaining people. There are already 7.7 billion people on the planet and by 2050, this number will rise to nine billion [19], creating unprecedented demand for food. Just 300 years ago, the global population was one billion people and farmers’ tools were simple [20,21]. Around 6000 BC., Egyptian farmers used a simple hoe to remove stones and dig holes for planting [22]. Later, oxen were used to draw wooden plows, but scarcely any changes were made to the plough for millennia. However, there were changes in the animals that pulled them, e.g., from oxen to camels and horses. After ploughing, fields were harrowed to prepare the seedbed for sowing, but this method left seeds behind on the surface and resulted in low yield [23].

Three-field crop rotation helped farmers minimize the risk of crop failure and famine. In this system, one-third of fields were sown in autumn with winter-hardy grain crop and one-third were used for e.g., potatoes for autumn harvest. The remaining one-third of fields were left fallow, to regenerate soil fertility [24]. Using the three-field system, farmers could produce two harvests a year, so they could keep their family and community fed year around. In the 18th century, an indispensable hand tool in Europe was the scythe [25], which was used for harvesting low-growing plants but was not suitable for all terrain [26]. For regions with tall vegetation, a machete was used [27]. Farmers in Egypt still use a machete-like tool to harvest sugarcane today [28]. Harvesting must be done quickly, to allow maximum juice to be extracted from the sugarcane [29].

Apart from tools, agriculture also needs fertile soil and water. In Egypt, these are provided by one of the world’s longest rivers, the Nile, which rises in Ethiopia and has been replenishing the soils of the Nile delta with vital nutrients for millennia [30]. Around 5000 years ago, Egyptian farmers developed a sophisticated irrigation system for their fields and to this day, pumps direct the nutrient-rich Nile water into a wide network of channels [31]. However, flow in the Nile river is declining and, with increasing groundwater extraction, the soil is becoming salinized [32]. Farmers are currently remedying this by applying more fertilizer [33], which in the long-run causes further damage to the soil [34]. This problem is not limited to Egypt, but is a global issue.

In January 2018, Cape Town almost reached “day zero” [35], when no more water would flow through the water mains [36], but strict water-conserving measures were able to defer water shut-off. Heatwaves are one of the main reasons for the falling water level [37]. Month for month, new record temperatures are being set around the world. In 2019, Paris reached a new record high of 42.6 °C [38], while in New Delhi temperatures rose to 48 °C. Across the globe, extreme heat is

Fig. 1. Hyper-automation technologies used in farming [12].

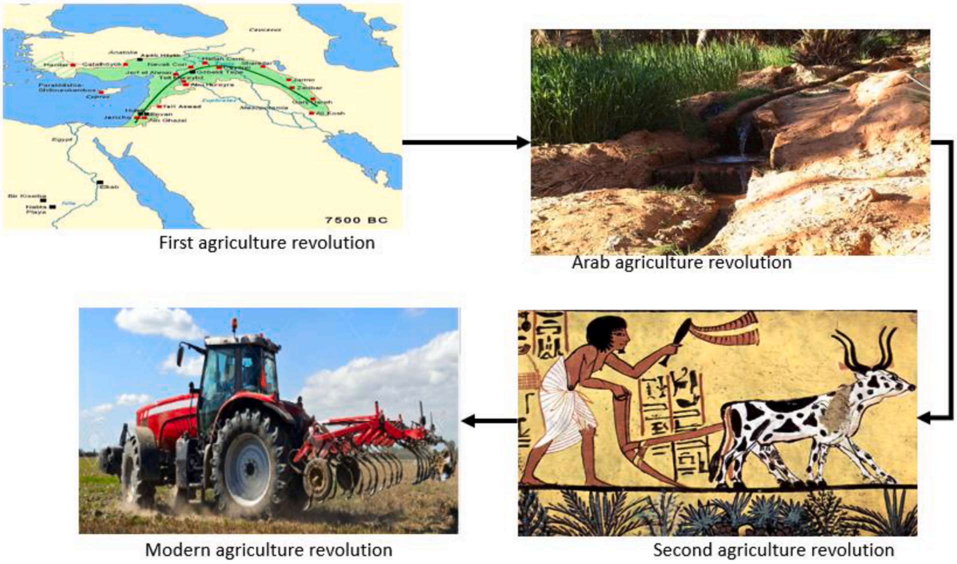


Fig. 2. Farming revolutions throughout history [16].

destroying 18–42 % of crops, depending on the robustness of the plant type [39]. Farmers are also seeing increasing environmental challenges, such as soil degradation, falling groundwater levels, and course more unpredictable weather fluctuations because of climate change. Another problem for farmers is lack of farm land [40]. In Brazil, more fires are breaking out in the Amazon rainforest than ever before, which climate activists believe is due to illegal clearing fires being started to make room for larger fields and cow pastures [41]. The Amazon, the world's largest rainforest, has an important function as the earth's 'lungs', since plants absorb the greenhouse gas CO_2 and convert it into oxygen [42]. Fires, on the other hand, emit CO_2, further heating up the earth.

Greenhouse gases are one of the causes of global warming, and the main producer of these gases is agriculture, not just because of forest clearing [43]. The other main producer is the transport sector. If we continue to produce greenhouse gases at the current rate, the Earth will warm up by approximately 4.5 °C by 2100 according to forecasts based on data from the Intergovernmental Panel on Climate Change (IPCC).

However, it is not too late, as we are on the verge of an agricultural revolution. Hyper-automation [44] can help overcome the climate crisis and the growing demand for food. For example precision farming involves harnessing data obtained using many sensors in specific crop fields, crops, but also weather data, etc., and using these data to maximize yield [45]. Scientists at the University of Bonn) have developed a precision farming tool called "Crop Watch" which helps to use as little water, fertilizer, and pesticides as possible while keeping yield stable despite unpredictable weather. Soil moisture level and plants are monitored using sensors and a drone equipped with a camera that takes photos of each single plant in the field [46]. A mobile weather station provides weather data. Instead of performing field inspections to determine the incidence of pests and diseases, which is problematic on large-scale farms, farmers can use data from Crop Watch to assess the risk [47]. This new technology can recognize problems at an early stage, long before a professional farmer would see that something is amiss.

However, not all farmers will want to use new technologies on their own, so the realistic solution would be some kind of service package where farms could hire a small team along with the equipment that harvests the data [48]. Hyper-automation is likely to replace many humans in farming in the future, as happened in the 19th century in the UK with the onset of the Industrial Revolution. A machinery revolution is a distinguishing feature of agriculture [49], e.g., the change from a basic wooden plough to the giant reversible metal ploughs of today [50]. These provide the advantage of not only breaking up the soil, but turning it, which kills weeds [51]. They also rely on mechanical power, rather than draft animals [52,53].

The changes brought by the Industrial Revolution attracted people into cities to find better paid jobs, greater prosperity, and educational opportunities for their children. Throughout Europe and the USA [54], farms are now being abandoned in a growing trend for urbanization [55]. Human manpower of farms has been replaced through mechanization [56]. Some farmers own a fleet of machines, while other use rental services [57]. The early problems with such machinery have generally been resolved by new technology [58,59].

Demand for reliable agrarian machines is still growing [60–62]. New and improved tractors facilitate farm work, from coffee harvesting in Brazil to ploughing rice paddies in Laos. Today it takes just one person to drive a tractor with a 12-cylinder engine that sends 600 horsepower to its wheels. Hybrids have been made and farm machinery now has smart systems that help with the cropping [63]. However, it is clear that' bigger, faster, further' is reaching its limits, as arable land and water are becoming more scarce and soils are becoming infertile. Now, the perception is that less is actually more and that we must rethink farming practices, e.g., make a move to Agriculture 4.0/5.0 and hyper-automation.

Apart from machine size, use of water and chemicals is undergoing a paradigm shift to 'less is more' [64]. For example, Crop Watch focuses on targeted, and thus economical, use of water and chemicals by using field data to look for recurring patterns that point to problems [65]. If a plant is less green than expected, this may indicate disease, as chlorotic spots and necrotic tissue make it look yellowish or brown [66]. It is precisely these areas that the farmer wants to identify. The Crop Watch software analyzes the data and provides information to the farmer on a smartphone [67]. To prevent this data from falling into the hands of third parties, it is stored locally on a server that only the famer can access. Programs like Crop Watch are powerful tools that enable very targeted decisions about the use of water, fertilizer, and pesticides [68]. In the future, technology will help farmers to cut their water use by up to 50 % and their use of pesticides by up to 90 % [69]. Hyper-automation enables solutions that are better for the environment [70], while minimizing resource use. However, farmers cannot dispense with pesticides entirely at present, in conventional or organic farming, partly because of pest problems, but also because consumer expectations are very high [71]. Most consumers like e.g., apples to be perfectly round and shiny, not bumpy with holes, making it necessary to use various chemicals to avoid pest damage. Crop plants have been bred over time to produce higher yields and new techniques make it possible to manipulate plant DNA directly. However, these new super-plants also have drawbacks, as many modern crop plants are highly susceptible to diseases and insect infestation, so farmers must spray them with pesticides [72].

Insect-related disease epidemics in humans led to the development of new insecticides [73]. Early efforts to develop an insecticide with long-lasting effect that was non-toxic for humans and could be cheaply produced [74] led to the development of the infamous DDT in 1939 [75]. At that time, diseases such as malaria and typhus, which are spread by pests and insects like lice and mosquitoes, were rife [76] and DDT seemed the perfect solution [77]. It was used in spray cans to target body lice [78] and on farms to increase food production. However, when DDT became available on the free market, scientists discover that some insects had developed resistance to it. Even more worrying, they found traces of DDT in food [79]. The American biologist Rachel Carson was the first to publicly criticize the use of DDT and other insecticides. A US committee [80] investigating her data vindicated her results, but 120 countries only banned the use of DDT in 2001 [81]. It is now only used in a few countries, such as India, to fight malaria. Some environmentalists argue that banning particular compounds is not a solution because farmers may replace them with even more toxic chemicals [82]. Hyper-automation offers a solution by identifying areas of fields that actually need treatment with chemicals (pesticides or fertilizers) [83]. This saves money and spares the environment.

Customized treatments are also needed for farm animals [84]. Livestock have played an important role in the history of agriculture, but animal husbandry has always been problematic [85]. Livestock act as reservoirs for diseases, which can easily spread through the herd, and increased domestication of farm animals has actually made them more susceptible to disease. The longer humans and animals live together, the greater the likelihood that they will transmit diseases to one another. For example, geneticists believe that the measles virus emerged from rinderpest [86]. However, while almost all humans survive measles, about 90 % of cows die from rinderpest. In countries where people depend on cattle for their livelihoods, this disease can cause hunger and starvation. In 1715, Lancisi published instructions which still hold true centuries later [87]. These include culling sick cattle, covering cadavers with lime, quarantining contagious herds, and banning the transport of animals.

Animal diseases continue to be a constant threat [88], but have also led to medical breakthroughs. When a country doctor called Edward Jenner noticed that people who had caught and recovered from cow pox never contracted smallpox [89], he began a set of experiments that resulted in the invention of vaccination. Vaccination has since saved many lives and has enabled control of many human diseases and animal diseases [90]. A consistent vaccination strategy against rinderpest led to eradication of this disease in 2011.

However, it is clear that limits need to be set when it comes to veterinary medicine, as e.g., antibiotics are still used to plump up pigs and make dairy cows more productive [91]. This particular use is prohibited by many nations, but a WHO study of animal health in 2019 showed that almost one-third of 155 participating nations were still using antibiotics as a growth booster. Such routine use of antibiotics has led to antibiotic resistance [92] and in fact there are no longer effective drugs against some microbes that cause human and animal diseases. There are other alternatives for disease prevention in livestock animals. One solution lies in hyper-automation in animal houses [93,94], where farmers rely on technology rather than drugs to improve cow health and increase milk production, which is critical for dairy farm survival in an era of low prices [95]. Hyper-automation results in a fully-automated cowshed the offers a lot of room, light, and fresh air, factors that relax the cows and reduce the incidence of stress-related injuries [96]. An automated feeding belt saves space and replaces manual labor, while a fully-automated grid system herds the cows into a modern rotary milking parlor with robot milkers [97]. The earliest rotary parlor (from 1930) could milk 50 cows in 12.5 min, but humans still needed to attach the milkers by hand [98]. A milk carousel introduced on a pioneering farm in Germany in 2017 can accommodate 56 animals and milks 250 cows in just one hour, almost completely without human help [99]. An infra-red camera scans the udder and navigates the milkers to the teats. Before attachment, the robot cleans and preps the udder, improving hygiene and preventing infection. At the same time, it checks the cow's health. Each animal has a digital patient file and if the system finds indications of disease, it issues a red alert. An employee promptly checks on the cow and takes any measures needed. These new technologies reduce labor costs, increase milk yield, and improve the health of the dairy cows, while reducing the amount of medications dispensed by 30 % [100]. A drawback is that in future, technology nerds could replace animal-loving farmers [101].

Organic farming offers another way to decrease the use of drugs in livestock farming. On organic farms, a sick animal must first be treated with natural remedies or homeopathy before resorting to conventional pharmaceuticals [102]. Organic farming involves dealing sustainably with natural resources, an objective that organic farmers have in common with hyper-automation. Since this technology is still in its infancy, some suggest that organic farming could be a quick solution to the climate crisis. A study in the UK concluded that if all British agriculture shifted to organic, this would result in a 24 % reduction in greenhouse gas emissions, but crop yields would also decline considerably [103]. This would require food imports to increase, bringing with them the greenhouse gas costs of producing that food, but also of shipping it, so switching to organic farming cannot be the sole solution [104]. If consumers were to eat less meat, fish, and dairy products, and instead eat more vegetables and nuts, local organic farmers could probably supply sufficient food. Hyper-automation can solve all these apparently conflicting demands [105]. One ambitious project, run by the University of Bonn, involving a robot called “phenoRob”, is taking up the fight against the climate crisis and the growing demand for food. The prototype robot can gauge the kind of customized treatment a plant needs and take on-the-spot action. The first task is to teach the robot how to deal with weeds, where information must be conveyed to the robot on the difference between useful and bad plants. This is a difficult task, since the robot has only milliseconds to decide if the plant is desired or unwanted if it is to handle an entire field [106]. Target localization is crucial in autonomous robot farming, because if the robot misses a small, tiny plant that is trying to grow then use of the robot is pointless [107]. Another team at the University of Bonn is working on getting the robot to recognize its location. For this, a drone surveys the field and sends a map to the robot that allows it to navigate to accuracy of 2 cm [108]. Currently, no other machine is capable of greater accuracy. Once the robot knows where to look for weeds, it moves across the field and recognizes the surface. Whenever it discovers weeds, it activates a precision laser and zaps them to dust [109], making pesticides superfluous.

Smart robots could revolutionize farming and guide it into a new era of “less and smaller is more” [110]. Large agricultural machinery still dominate farming, but these machines weight tons and cannot be used everywhere. Light, agile robots can solve this problem and the landscape will probably look different once they are deployed [111]. Small agrarian robots can cultivate and harvest not only in large level fields but also in difficult terrain, small fields, and fields with hedges and wildflower verges where bees and other beneficial insects live. Hyper-automation has the potential to bridge the gap between conventional and organic agriculture [112], by relying on chemicals to kill weeds [113]. Around the world, other scientists are developing drones and robots that can cultivate fields autonomously. With hyper-automation, scientists are introducing new technology to help in fighting climate change and preventing future food shortages [114].

3. Methods

Secondary data collection for the present analysis comprised four steps (Fig. 3). An initial literature review was performed in order to

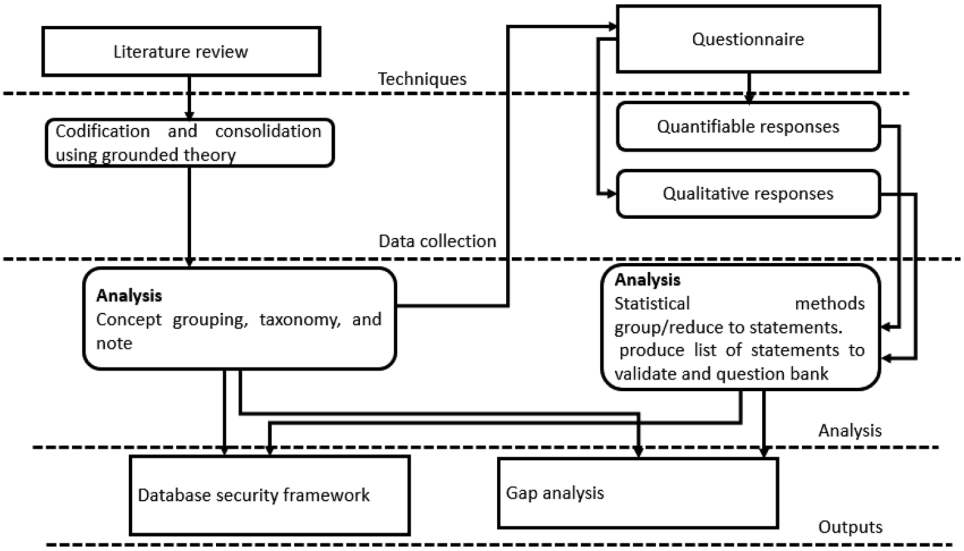


Fig. 3. Mind map showing inputs and outputs of the current analysis.

gather data. The results were codified and consolidated using grounded theory and then analyzed by concept group, taxonomy, and notes The results were analyzed by statistical methods, grouping or reducing the statements, producing a list of statements to validate, and a question bank.

Searches for relevant articles for the literature review were made in SCOPUS, Dimension, PubMed, WOS (Web of Science), Crossreff, and Google Scholar, using various search keywords and key words. After comparing the hits, duplicate papers were removed (Fig. 4). A slicer filtering technique was used in Microsoft Excel to process the remaining documents. We started by downloading a lot of articles and saving them as CSV files and then arranged the various pieces according to year of publication. We also considered the titles of the journals. The information was arranged into cell arrays of papers published since 2000. Older publications were excluded.

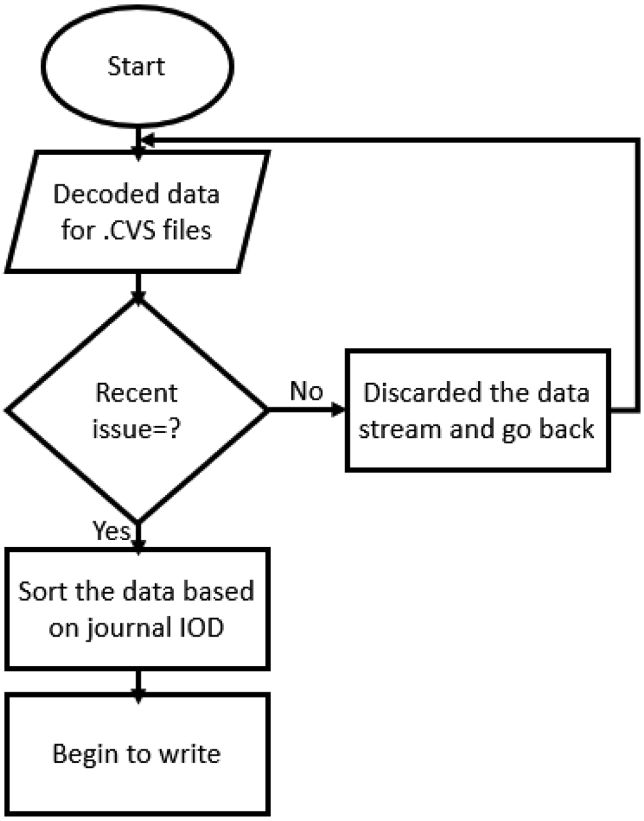


Fig. 4. Flowchart of data testing.

4. Results and discussion

Modernizing the agriculture sector is a key component in growth of a country's economy and agricultural resource management is currently the most complex challenge [115]. Water management is particularly important, as 70 % of fresh water is used in the agriculture sector. Water is critical in some parts of agriculture, such as cropping. In one existing solution, an Internet of Things [116] gateway is utilized to link field devices, which may be remote-controlled or WAN (wide area network), to wireless internet networks [117]. This module can interface with several sensors, e.g., for measuring temperature and humidity [118]. It also has provision for a GSM-based scheduled watering arrangement, which enables efficient use of soil properties and crop organization. In order to verify that the system is functioning properly, users must first register with an administrator [119], who verifies the information submitted by the user and grants access to manage the system. A sensor is used to transmit data to Google spreadsheets, which store data related to protected crops as well as real-time information [120]. This modular system is ideal for crop selection based on soil quality and fully eliminates unnecessary water waste into modules [121].

4.1. Current applications of automation and robotics in agriculture

Farmers are able to successfully manage crop output while using less energy and money through automation of some procedures. Researchers and farmers alike are becoming interested in developing automation systems for agriculture due to scarcity of agricultural labor, an aging farmer population, and rising agricultural wages. Autonomous robots and agricultural equipment, such as drones and mobile robots, often equipped with cultivators, planters, cultipackers, and chisel plows, have been crucial advances in agricultural automation [122]. The drones, humanoid robot, and mobile robots depicted in Fig. 5 are examples of equipment that can be automated to improve agricultural productivity. There are many different ways that automation and robotics can be used in agriculture. Depending on the type of land and activity required, different robotics and vehicle structures must be used to carry out agricultural operations. Every robot and vehicle structure has a set of limitations that need to be addressed with different equipment [123].

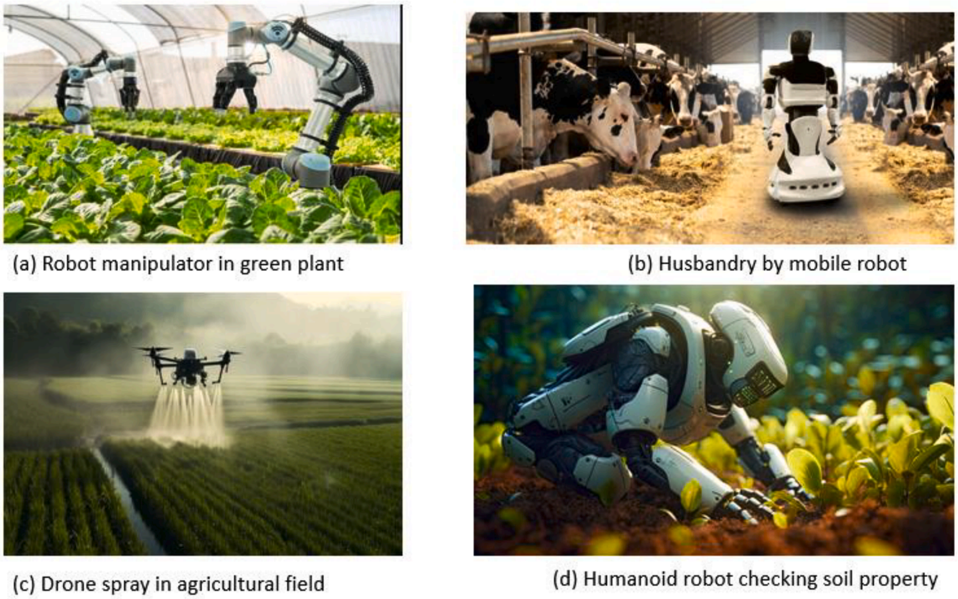

(a) Robot manipulator in green plant
(b) Husbandry by mobile robot
(c) Drone spray in agricultural field
(d) Humanoid robot checking soil property

Fig. 5. Hyper-automation systems in agriculture [125].

Due to its sensitivity to mud and wetness, the robotic structure is limited in its ability to perform harsh agricultural chores. Since the tractor has less sensitive electronic circuits and a strong ability to maneuver through muddy structures, it is used to carry out this work, but the large size of modern tractors limits their use to large areas [124]. A mobile robot is required to work in more limited areas. Drone applications are limited to open spaces and have little use in enclosed spaces like greenhouses because of the risk of collisions.

Crop establishment involves placing seeds or young plants into the ground. However, different plant species need different seed spacing in order to maximize output and optimize growth, which calls for a high level of precision in seeding. An effective autonomous system must guarantee creation of straight plant rows and prevent any seed planting errors. For a number of crops, including maize, wheat, sugarcane, and vegetables, autonomous systems have been offered as a solution to the issues associated with human planting. Several factors have emerged as the primary design goals in order to create an effective autonomous system for the planting process. The robot or vehicle must first be able to travel precisely in a straight line, even on uneven farm fields. This ability is crucial because it guarantees the effectiveness of the automation process in subsequent tasks, such as harvesting or inspection.

Determining the amount of soil moisture is the second prerequisite, since it can impact the seeding process. Certain seeds require precise seeding depth, so soil moisture content and compaction must be taken into account to maintain constant placement depth. Lastly, a seed detection feature is required, where the system can identify the presence of seed and guarantee that there are no unplanted areas, with the primary goal of ensuring that the seed is planted at constant depth and spacing.

Most seeding research to date has concentrated on the creation of autonomous systems that maintain the required seed spacing and depth. In some research, an infrared (IR) sensor has been used to detect rows and has given satisfactory precision in seed spacing. To facilitate consistent planting, a control system for seed-metering units has been developed. A seed metering device is typically used in the planting process to measure the amount of seed that is released into the soil [126]. Before seed is planted at the scheduled precise intervals, a device is typically utilized to classify the seed into a single or group of seeds. Different speeds and seed spacing are measured to assess the effectiveness of the seed metering device, while plant spacing uniformity, row variation, fuel consumption, and negative slippage are used to gauge the quality of seeding. The results indicate that more effective seed metering unit design can result in improved planting quality and a 22 % increase in fuel savings [49]. Using global positioning system (GPS) is another way to guarantee consistent seed spacing. With the use of combined sensing technologies from the Global Navigation Satellite System (GNSS) and the Inertial Measurement Unit (IMU), a control system for seed and fertilizer has been developed. In this system, the vehicle carries out the operation by comparing the goal parameter with time and space data gathered from the GNSS/IMU, depending on the target application rate of seed and fertilizer. It has been demonstrated that this application is effective, with a maximum error of 4.9 % at 5.8 km/h. A variable-rate seeding control system for maize planters based on GPS is also presented in the literature [127]. Real-time seeding position, travel speed, and course angle are located in this application using a GPS receiver operating at a set frequency. Additional processing is performed on the GPS data to determine the latitude, longitude, course angle, and travel speed. The average seeding accuracy of this implementation is 97.6 %, making it an effective variable-seed control system at a reasonable cost. In addition to employing GPS, a high-speed camera has been designed to ensure uniform seed spacing during the seeding process. This approach uses a Fuji F660EXR camera, attached to the Unisom pneumatic planter output, to monitor the seed falling trajectories at a sustained pace of 320 frames per second. The results demonstrate that seed spacing uniformity is very efficient at 95 % confidence level in a speed range 3–4.5 km/h. To determine the rate at which chickpea, wheat, and alfalfa seeds are sown in planters, an infrared sensor system including photo diodes and infrared light-emitting diodes (IR LEDs) has been developed [128]. This method involves translating the light-receiving sensor’s output voltage into an analog value, which is subsequently processed into a model to determine the sowing rate. This method achieves significant accuracy in measuring the sowing rate, with a coefficient of 0.94 for model determination. Since planting is the initial step in the agricultural operation, it is crucial for the consistency of the entire automated system. Subsequent activities, which rely on the plant distribution established during the planting procedure, will suffer if the operation is carried out inconsistently. Development of an efficient planter that can recognize seeds will enable an optimal planting procedure at a minimal operational cost, while simultaneously preserving uniform seed distribution over the field. The automation of the planting process will thereby make farming much more convenient and efficient in the future.

4.2. Crop inspection

In arable farming, inspection refers to the process of looking for illnesses or other flaws in crop plants. Plant diseases are the main cause of productivity declines in cropping and result in financial losses. Due to the highly dynamic nature of the agricultural environment, a variety of unanticipated and atypical stress circumstances, including variations in temperature, humidity, water levels, the advent of diseases, and pests, have an impact on plants and their output [32]. Serious and irreversible harm may result if those anomalies are not treated right away. Farmers formerly used their vision to detect any anomalies in the plant during field inspections, but the efficiency of this form of inspection is limited [129]. A system that can carry out the inspection procedure in place of human vision is needed for the automation of agricultural inspection. Computer vision has become a popular option in agricultural plant inspections. This advanced image processing technology has the potential to replace human vision in some detailed tasks related to inspection processes [130]. The growth in image processing and computer vision applications in agriculture can be attributed to lower equipment prices, more computing power, and growing interest in non-destructive food inspection techniques. Most vision system applications in agriculture are used to identify diseases, while some are used to verify the quality of products [131] (Fig. 6).

Measured parameters utilized in design of an effective variable-rate spraying system, a component of an autonomous agricultural spraying system for disease management, are displayed in Table 1. Different plant species and spraying requirements lead to different parameter choices when creating a variable-rate spraying strategy. The volume and flow rate of the spraying agent employed in the spraying operation is computed based on those characteristics. Compared with canopy or homogeneous spraying methods, variable-rate spraying has been shown to reduce pesticide consumption by up to 85 %. It also avoids direct dangers to farmers through the use of harmful chemicals.

Four distinct vision systems for target recognition in agricultural harvesting are summarized in Table 2.

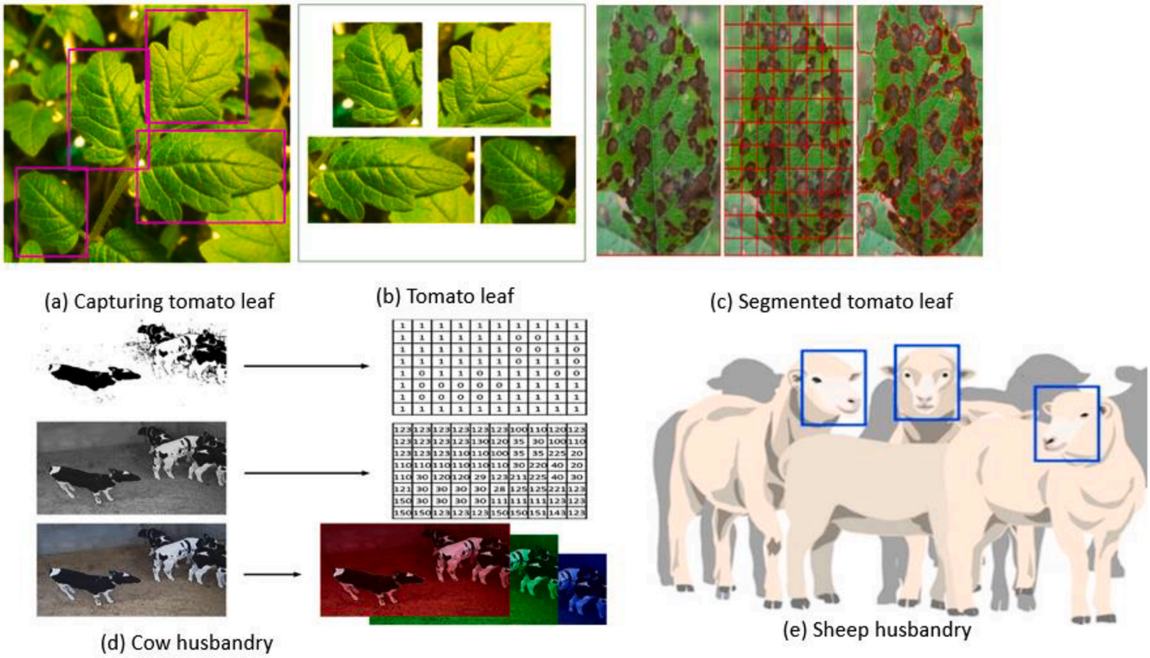
An overview of the elements taken into account when creating the end effector for an effective grabbing mechanism that preserves the quality of the harvested product is provided in Table 3. Multiple criteria are involved, with consideration given to the physical attributes and structural make-up of the harvested product. In order to preserve product quality during the harvesting process, gripper designs and mechanisms for various applications must be specially created. In agriculture, harvesting is a critical task since, because the harvested product is delicate, the manner in which it is collected will also have an impact on its quality. Even if the plants receive proper care during the growing season, there is still no guarantee that the output will be of high quality because robotic and automated harvesting methods run the risk of damaging the crop. In order to ensure that the efficiency of robotic and automated applications in the harvesting process is comparable to or better than that of humans laboring to harvest the agricultural product in a timely manner without compromising its quality, a great deal of research is being done.

Table 1
Parameters used in designing a variable rate spraying method.

Refs.	Disease/Detection	Parameter(s) used
[134]	Greenhouse crop diseases	Volume rate, target location and airflow rate
[135]	Weed removal in carrot farm	Weed species and size
[136]	Vineyard spraying operation	Sprayer travel speed and position (latitude, longitude)
[137]	Poplar diseases	Sprayer configuration, mix of nozzle types, airflow rates, and air direction
[138]	Nitrogen fertilization in greenhouse crops	Using picture attributes (entropy, energy, and spatial homogeneity) to determine plant needs and requirements
[139]	Grape leaf diseases	Leaf RMS velocity, average leaf velocity, turbulence level, front and rear side spray coverage, and droplet density
[140]	Weed removal in wheat	Weed spatial distribution
[141]	Flower pollination	Gravity, wind and drag
[142]	Grape powdery mildew	Level of diseases

5. Conclusions

Around 70 % of the fresh water used worldwide is used in agriculture, but much of this water is lost due to poor design of irrigation systems. Using incorrect dosages of fertilizers and insecticides also contributes to wasteful use of resources. It can also result in soil



1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	0	0	1	1
1	1	1	1	1	1	0	0	1	0
1	1	1	1	1	1	0	1	1	0
1	0	1	1	0	1	1	1	0	0
1	0	0	0	0	0	1	1	1	1
1	0	0	0	0	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1

123	123	123	123	123	123	100	110	120	123
123	123	123	123	130	120	35	30	100	110
123	123	123	110	110	100	35	35	225	20
110	110	110	110	110	110	30	220	40	20
110	30	120	120	29	123	211	225	40	30
121	30	30	30	30	28	125	125	221	123
150	30	30	30	30	111	111	111	123	123
150	150	123	123	123	150	150	151	143	123

Fig. 6. Use of computer vision applications in inspection of (a-c) tomato plants, (d) cow husbandry, and € sheep husbandry [132,133].

Table 2
Vision schemes for agricultural harvesting target detection.

Vision Scheme	Functions	Advantages	Disadvantages
[143, 144]	Use color, shape, and texture to pinpoint target location.	Easiest and least expensive	Accuracy of detection will changes with illumination.
[145, 146]	Determine target location by color, shape, and texture and localize the target fruit	Able to acquire the identified object's 3D feature	Requires expensive computing, costly sensor calibration, and unavoidable 3D measurement error.
[147, 148]	Determine target location using spectroscopic and image information extraction	Capable of identifying the intended object in a convoluted and unorganized work area	Costly sensor and computationally intensive picture processing.
[149, 150]	Determine target location by extracting 3D object feature	Able to obtain a 3D feature under different lighting circumstances	Large image data is needed for precise 3D visualization.

Table 3
Factors considered in the design and mechanism of harvesting robot grippers.

Refs.	Plant type	Factors considered
[151]	Strawberry	Target positional and localization error
[152]	Tomato	Human factors (body height, shoulder tip, waist and knee height)
[153]	Tomato	Grasping velocity, input force, contact time, and gripper stiffness
[154]	Kiwifruit	Target position accuracy and grasping pressure
[155]	Capsicum	Position and angle between plant parts
[156]	Citrus	Stalk orientation and harvesting posture
[157]	Pumpkin	Target orientation and compression yield force

pollution, which lowers crop productivity. Farmers will continue to make the same mistakes unless they are provided with accurate data on the amount of fertilizer required to enhance agricultural yield.

This paper evaluated application of hyper-automation in agriculture, using secondary data obtained in an in-depth literature review. Food is a primary human need and the global population has doubled in recent times, creating challenges for agriculture in feeding all. For this reason, farmers are looking to apply more advanced technology, such as hyper-automation, in the agriculture sector. According to our analysis, water management is the most crucial task in agriculture, followed by reduced use of farm inputs. Hyper-automation can provide some solutions, e.g., crop planting quality can be enhanced and fuel savings of 22 % can be made by using a more efficient automated seed metering unit.

6. Limitations and possibilities for hyper-automation in agriculture, and recommendations

6.1. Limitations of hyper-automation

Limitations to the introduction of hyper automation in agriculture include high initial investment costs, potential job displacement, technological complexity, and the need for reliable internet connectivity in rural areas. Concerns about data privacy and cybersecurity may also pose challenges for widespread adoption. Other limitations are that:

- The risk of data privacy violations with artificial intelligence vendors requires investments in solutions like data masking and well-designed security infrastructures to avoid violations.
- Unavailability of synthetic datasets for model training in data generation can slow down operations.
- Systems based on artificial intelligence can contain biases based on assumptions embedded into training data or algorithms.
- Undocumented processes or ill-documented operations lead to a lack of process understanding, causing difficulties in effective analysis.
- The mindset of "avoiding all potential errors" slows down the adoption of hyper-automation.
- There is a need for user-friendly solutions that allow humans to step in so that automation can be successful.

6.2. Opportunities with hyper-automation

Image processing algorithms can identify and measure a variety of plant illnesses, nutrient shortages, and stress situations by examining the spectral reflectance characteristics of plants. The results of these algorithms are processed by low-code hyper-automation systems in the cloud, which provide actual actionable information to assist agronomists and farmers in making well-informed decisions about pest management, fertilization, and irrigation. Future smart agriculture will heavily rely on robots and drones, which provide a number of benefits such as energy efficiency, precision agriculture capabilities, environmental sustainability, and integration with smart technologies. Through integration with renewable energy, sustainability and environmental benefits, energy efficiencies, and additional benefits in the advancement of agriculture, these will play an increasingly important role in transforming agriculture into a smarter and more efficient industry as the world moves towards a more technologically advanced and sustainable future.

Mobility IoT-enabled field and crop monitoring devices are connected to a hyper-automation platform, which uses data analytics to give farmers real-time insights and recommendations about the health of their crops. Communication service providers are essential in carrying internet routes and connecting businesses to the world's cloud giants. Data collected e.g., by unmanned drones fitted with IoT sensors and cameras can then be utilized to determine the intensity of spraying in places most in need of attention. This strategy empowers farmers by providing them with accurate and timely information to improve their crop management techniques.

Data is a key component of smart agriculture, and low-code hyper automation platforms can be leveraged to create the data analytics tools that farmers need to detect patterns and trends in pest and disease outbreaks. Farmers can take prompt action and stop additional harm to their crops by using these systems, which send real-time notifications. Furthermore, farmers can adapt their farming operations to minimize crop destruction risk, optimize production, and cut waste with the use of real-time data analytics and advice. Farmers can also benefit from climate change and weather variability.

6.3. Recommendations

To fully reap the benefits of hyper-automation, organizations need to overcome a number of inherent difficulties. In order to address these issues, companies should make investments in retraining staff members to handle the new procedures and technologies, guarantee robust data security and governance protocols, foster efficient teamwork and communication, and continuously assess and modify their hyper-automation plans. We make the following recommendations on hyper-automation applications in agriculture:

- For researchers, it is important to focus on integrating ground robots with drones and enhance communication between multi-robot systems and agriculture items such as crops and husbandry, in order to make the most effective use of hyper-automation.
- Since there will be nine billion people on the planet by 2050, it is important to concentrate on hyper-automation technologies in all wealthy nations.

- Hyper-automation technology is especially important for developing nations, such as all of Africa. Due to their much larger populations than any other country in the region, Nigeria and Ethiopia will be important players.
- If all countries do not introduce hyper-automation, it will be difficult to feed a population of nine billion population, compromising global food security.

CRediT authorship contribution statement

Sairoel Amertet: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Girma Gebresenbet:** Project administration, Funding acquisition, Writing – review & editing, Writing – original draft. **Hassan M. Alwan:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declared that there is no conflict of interest.

Data availability

The data that has been used is confidential.

References

[1] L. Klerkx, E. Jakku, P. Labarthe, A review of social science on digital agriculture, smart farming and agriculture 4.0: new contributions and a future research agenda, NJAS-Wagening. J. Life Sci. 90 (2019) 1–16, 100315.

[2] B. Ozdogan, A. Gacar, H. Aktas, Digital agriculture practices in the context of agriculture 4.0, J. Econ. Finance Account. 4 (2) (2017) 186–193.

[3] B. Basso, J. Antle, Digital agriculture to design sustainable agricultural systems, Nat. Sustain. 3 (4) (2020) 254–256.

[4] S. Hackfort, Patterns of inequalities in digital agriculture: a systematic literature review, Sustainability 13 (22) (2021) 1–18, 12345.

[5] É.L. Bolfe, et al., Precision and digital agriculture: adoption of technologies and perception of Brazilian farmers, Agriculture 10 (12) (2020) 653.

[6] A. Lajoie-O'Malley, K. Bronson, S. van der Burg, L. Klerkx, The future (s) of digital agriculture and sustainable food systems: an analysis of high-level policy documents, Ecosyst. Serv. 45 (2020) 101183.

[7] Y. Sinitsa, O. Borodina, O. Gvozdeva, E. Kolbneva, Trends in the development of digital agriculture: a review of international practices. *BIO Web of Conferences*, EDP Sciences, 2021, p. 00172. Accessed: Apr. 17, 2024. [Online]Available: https://www.bio-conferences.org/articles/bioconf/abs/2021/09/bioconf_fies2021_00172/bioconf_fies2021_00172.html.

[8] J. Ingram, et al., What are the priority research questions for digital agriculture? Land Use Policy 114 (2022) 105962.

[9] M. Kern, Digital agriculture, ISPSW Strategy Ser. Focus Def. Int. Secur. 331 (8) (2015). Accessed: Apr. 17, 2024. [Online]Available: https://www.zef.de/fileadmin/user_upload/4saengenendt_download_331%20Digit%202015_Kern%5B1%5D.pdf.

[10] D.M. de Queiroz, A.L. de F. Coelho, D.S.M. Valente, J.K. Schueller, Sensors applied to digital agriculture: a review, Rev. Ciênc. Agronômica 51 (2021) e20207751.

[11] N. Chergui, M.-T. Kechadi, M. McDonnell, The impact of data analytics in digital agriculture: a review, in: Proceedings of the International Multi-Conference on: "Organization of Knowledge and Advanced Technologies"(OCTA), IEEE, 2020, pp. 1–13. Accessed: Apr. 17, 2024. [Online]Available: https://ieeexplore.ieee.org/abstract/document/9151851/.

[12] S. Fountas, B. Espejo-García, A. Kasimati, N. Mylonas, N. Darra, The future of digital agriculture: technologies and opportunities, IT Prof 22 (1) (2020) 24–28.

[13] Y. Liang, X. Lu, D. Zhang, F. Liang, Z. Ren, Study on the framework system of digital agriculture, Chin. Geogr. Sci. 13 (1) (2003) 15–19, https://doi.org/10.1007/s11769-003-0078-4. Mar.

[14] S. Jiang, J. Zhou, S. Qiu, Digital agriculture and urbanization: mechanism and empirical research, Technol. Forecast. Soc. Change 180 (2022) 121724.

[15] S. Tang, Q. Zhu, X. Zhou, S. Liu, M. Wu, A conception of digital agriculture, in: Proceedings of the IEEE International Geoscience And Remote Sensing Symposium, IEEE, 2002, pp. 3026–3028. Accessed: Apr. 17, 2024. [Online] Available: https://ieeexplore.ieee.org/abstract/document/1026858/.

[16] R.C. Allen, Tracking the agricultural revolution in England, Econ. Hist. Rev. (1999) 209–235.

[17] S.K. Balasundram, R.R. Shamshiri, S. Sridhara, N. Rizan, The role of digital agriculture in mitigating climate change and ensuring food security: an overview, Sustainability 15 (6) (2023) 5325.

[18] A. Salam, An underground radio wave propagation prediction model for digital agriculture, Information 10 (4) (2019) 147.

[19] O. Visser, S.R. Sippel, L. Thiemann, Imprecision farming? Examining the (in) accuracy and risks of digital agriculture, J. Rural Stud. 86 (2021) 623–632.

[20] O. Evans, "Digital agriculture: mobile phones, internet & agricultural development in Africa," 2018, Accessed: Apr. 17, 2024. [Online]. Available: https://mpra.ub.uni-muenchen.de/id/eprint/90359.

[21] N. Ivanova, M. Ovchinnikov, M. Lata, I. Korabelnikov, T. Kolmykova, E. V. Kharchenko, Digital agriculture: opportunities for the development of small agribusinesses and the respective problems, in: Digital Future Economic Growth, Social Adaptation, and Technological Perspectives, 111, Springer International Publishing, Cham, 2020, pp. 593–600, https://doi.org/10.1007/978-3-030-39797-5_56, in Lecture Notes in Networks and Systems, vol. 111.

[22] S. Shen, A. Basist, A. Howard, Structure of a digital agriculture system and agricultural risks due to climate changes, Agric. Agric. Sci. Procedia 1 (2010) 42–51.

[23] L. Xie, B. Luo, W. Zhong, How are smallholder farmers involved in digital agriculture in developing countries: a case study from China, Land (Basel) 10 (3) (2021) 245.

[24] M. McCampbell, C. Schumann, L. Klerkx, Good intentions in complex realities: challenges for designing responsibly in digital agriculture in low-income countries, Sociol. Rural. 62 (2) (2022) 279–304, https://doi.org/10.1111/soru.12359. Apr.

[25] E. Duncan, A.-R. Abdulai, E.D. Fraser, Modernizing agriculture through digital technologies: prospects and challenges, Handb. Hum. Impact Agric. (2021) 138–161.

[26] M.N.I. Sarker, M.S. Islam, M.A. Ali, M.S. Islam, M.A. Salam, S.H. Mahmud, Promoting digital agriculture through big data for sustainable farm management, Int. J. Innov. Appl. Stud. 25 (4) (2019) 1235–1240.

[27] B.C. Runck, A. Joglekar, K.A.T. Silverstein, C. Chan-Kang, P.G. Pardey, J. C. Wilgenbusch, Digital agriculture platforms: driving data-enabled agricultural innovation in a world fraught with privacy and security concerns, Agron. J. 114 (5) (Sep. 2022) 2635–2643, https://doi.org/10.1002/agj2.20873.

[28] P.P. Jayaraman, D. Palmer, A. Zaslavsky, A. Salehi, D. Georgakopoulos, I. Podnar Žarko, K. Pripužić, M. Serrano, Addressing information processing needs of digital agriculture with Open IoT platform, in: Interoperability and Open-Source Solutions for the Internet of Things, 9001, Springer International Publishing, Cham, 2015, pp. 137–152, https://doi.org/10.1007/978-3-319-16546-2_11, in Lecture Notes in Computer Science, vol. 9001.

[29] K. Rijswijk, L. Klerkx, J.A. Turner, Digitalisation in the New Zealand agricultural knowledge and innovation system: initial understandings and emerging organisational responses to digital agriculture, NJAS-Wagening. J. Life Sci. 90 (2019) 100313.

[30] B. Jabir, N. Falih, Digital agriculture in Morocco, opportunities and challenges, in: Proceedings of the IEEE 6th International Conference on Optimization and Applications (ICOA), IEEE, 2020, pp. 1–5. Accessed: Apr. 17, 2024. [Online] Available: https://ieeexplore.ieee.org/abstract/document/9094450/.

[31] L. Prause, Digital agriculture and labor: a few challenges for social sustainability, Sustainability 13 (11) (2021) 5980.

[32] A. Kayad, et al., How many gigabytes per hectare are available in the digital agriculture era? A digitization footprint estimation, Comput. Electron. Agric. 198 (2022) 107080.

[33] C. Weltzien, Digital agriculture or why agriculture 4.0 still offers only modest returns, Landtechnik 71 (2) (2016) 66–68.

[34] S. Chaterji, et al., Lattice: a vision for machine learning, data engineering, and policy considerations for digital agriculture at scale, IEEE Open J. Comput. Soc. 2 (2021) 227–240.

[35] S. Pearson, et al., Robotics and autonomous systems for net zero agriculture, Curr. Robot. Rep. 3 (2) (2022) 57–64, https://doi.org/10.1007/s43154-022-00077-6. Jun.

[36] M. Anitei, C. Veres, A. Pisla, Research on challenges and prospects of digital agriculture. Proceedings, MDPI, 2021, p. 67. Accessed: Apr. 17, 2024. [Online] Available: https://www.mdpi.com/2504-3900/63/1/67.

[37] A. Elbehri, R. Chestnov, Digital Agriculture in Action: ArtificiaI Intelligence For Agriculture, Food & Agriculture Org, 2021. Accessed: Apr. 17, 2024. [Online] Available: https://books.google.com/books?hl=en&lr=&id=uKJfEAAAQBAJ&oi=fnd&pg=PR2&dq=digital+agriculture&ots=o8UM94v_Gr&sig=yTc_pTILQ8GQH78akqw64nm0hDM.

[38] M.K. Sott, et al., A bibliometric network analysis of recent publications on digital agriculture to depict strategic themes and evolution structure, Sensors 21 (23) (2021) 7889.

[39] C. Stitzlein, S. Fielke, A. Fleming, E. Jakku, M. Mooij, Participatory design of digital agriculture technologies: bridging gaps between science and practice, Rural Ext. Innov. Syst. J. 16 (1) (2020) 14–23.

[40] E.A. Batishcheva, Y.A. Bezgina, O.S. Zinisha, N.A. Goncharova, I.V. Ryndina, Digital agriculture: current state, problems and development prospects, Res. J. Pharm. Biol. Chem. Sci. 9 (6) (2018) 1556–1561.

[41] A. Salam, Design of subsurface phased array antennas for digital agriculture applications, in: Proceedings of the IEEE International Symposium on Phased Array System & Technology (PAST), IEEE, 2019, pp. 1–5. Accessed: Apr. 18, 2024. [Online]Available: https://ieeexplore.ieee.org/abstract/document/9020918/.

[42] T.W. Griffin, K.D. Harris, J.K. Ward, P. Goeringer, J.A. Richard, Three digital agriculture problems in cotton solved by distributed ledger technology, Appl. Econ. Perspect. Policy 44 (1) (2022) 237–252, https://doi.org/10.1002/aepp.13142. Mar.

[43] Q.H. Ngo, T. Kechadi, N.-A. Le-Khac, Knowledge representation in digital agriculture: a step towards standardised model, Comput. Electron. Agric. 199 (2022) 107127.

[44] M. Carolan, Automated agrifood futures: robotics, labor and the distributive politics of digital agriculture, J. Peasant Stud. 47 (1) (2020) 184–207, https://doi.org/10.1080/03066150.2019.1584189. Jan.

[45] Y. Chen, Y. Li, C. Li, Electronic agriculture, blockchain and digital agricultural democratization: origin, theory and application, J. Clean. Prod. 268 (2020) 122071.

[46] J. Porciello, S. Coggins, E. Mabaya, G. Otunba-Payne, Digital agriculture services in low-and middle-income countries: a systematic scoping review, Glob. Food Secur. 34 (2022) 100640.

[47] T. Verdonk, L. Reins, Planting the seeds of market power: digital agriculture, farmers' autonomy, and the role of competition policy, in: Regulating New Technologies in Uncertain Times, 32, T.M.C. Asser Press, The Hague, 2019, pp. 105–132, https://doi.org/10.1007/978-94-6265-279-8_7, in Information Technology and Law Series, vol. 32.

[48] J. Zhou et al., "CropQuant: an automated and scalable field phenotyping platform for crop monitoring and trait measurements to facilitate breeding and digital agriculture," *BioRxiv*, p. 161547, 2017.

[49] R. Abbasi, P. Martinez, R. Ahmad, The digitization of agricultural industry–a systematic literature review on agriculture 4.0, Smart Agric. Technol. 2 (2022) 100042.

[50] M. Hidrobo, G. Palloni, D.O. Gilligan, J.C. Aker, N. Ledlie, Paying for digital information: assessing farmers' willingness to pay for a digital agriculture and nutrition service in Ghana, Econ. Dev. Cult. Change 70 (4) (2022) 1367–1402, https://doi.org/10.1086/713974. Jul.

[51] A. Salam, Subsurface MIMO: a beamforming design in internet of underground things for digital agriculture applications, J. Sens. Actuator Netw. 8 (3) (2019) 41.

[52] S. Nolet, Seeds of success: advancing digital agriculture from point solutions to platforms, U. S. Stud. Cent. Univ. Syd. Syd. NSW (2018). Accessed: Apr. 18, 2024. [Online]Available: http://united-states-studies-centre.s3.amazonaws.com/attache/1a/d0/a5/4e/af/c1/0a/6a/ab/5c/13/fe/ed/4f/99/9b/Advancing-Digital-Agriculture-in-Australia.pdf.

[53] A.K. Subaeva, M.M. Nizamutdinov, L.M. Mavlieva, M.N. Kalimullin, Labor productivity in digital agriculture, in: *Proceedings of the* BIO Web of Conferences, EDP Sciences, 2020, p. 00226. Accessed: Apr. 18, 2024. [Online]Available: https://www.bio-conferences.org/articles/bioconf/abs/2020/01/bioconf_fies2020_00226/bioconf_fies2020_00226.html.

[54] V. Bellon-Maurel, I. Piot-Lepetit, N. Lachia, B. Tisseyre, Digital agriculture in Europe and in France: which organisations can boost adoption levels? Crop Pasture Sci. 74 (6) (2023) 573–585.

[55] N.S. Kurnosova, S.A. Kurnosov, A.V. Ulez'ko, About models of agriculture digital transformation, in: Proceedings of the IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2021 012011. Accessed: Apr. 18, 2024. [Online]Available: https://iopscience.iop.org/article/10.1088/1755-1315/786/1/012011/meta.

[56] Á. Regan, Exploring the readiness of publicly funded researchers to practice responsible research and innovation in digital agriculture, J. Responsible Innov. 8 (1) (2021) 28–47, https://doi.org/10.1080/23299460.2021.1904755. Jan.

[57] S. Rotz, et al., The politics of digital agricultural technologies: a preliminary review, Sociol. Rural. 59 (2) (2019) 203–229, https://doi.org/10.1111/soru.12233. Apr.

[58] R. Bertoglio, C. Corbo, F.M. Renga, M. Matteucci, The digital agricultural revolution: a bibliometric analysis literature review, IEEE Access 9 (2021) 134762–134782.

[59] D.V. Aladin, E.V. Aladina, D.A. Chuvikov, O.O. Varlamov, L.E. Adamova, Creating a 'Logical intelligent plant care system' in digital agriculture based on Mivar approach, in: Proceedings of the IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2022 012004. Accessed: Apr. 18, 2024. [Online]Available: https://iopscience.iop.org/article/10.1088/1755-1315/954/1/012004/meta.

[60] E. Leonard et al., "Accelerating precision agriculture to decision agriculture: enabling digital agriculture in Australia," 2017, Accessed: Apr. 18, 2024. [Online]. Available: https://rune.une.edu.au/web/handle/1959.11/22748.

[61] E.V. Kotsur, M.N. Veselova, A.V. Dubrovskiy, V.N. Moskvin, Y.S. Yusova, GIS as a tool for creating a global geographic information platform for digital transformation of agriculture, in: Proceedings of the Journal of Physics: Conference Series, IOP Publishing, 2019 033009. Accessed: Apr. 18, 2024. [Online]Available: https://iopscience.iop.org/article/10.1088/1742-6596/1399/3/033009/meta.

[62] H. Yoo, D. Baek, S. Choi, Navigation path following platform for a greenhouse shuttle robot using the state-flow method, Math. Probl. Eng. 2024 (2024). Accessed: Feb. 25, 2024. [Online]Available: https://www.hindawi.com/journals/mpe/2024/8810990/.

[63] K.A. Vasilyevich, Machine learning methods in digital agriculture: algorithms and cases, Int. J. Adv. Stud. 8 (1) (2018) 11–26.

[64] J.C. Moreno, et al., A pending task for the digitalisation of agriculture: a general framework for technologies classification in agriculture, Agric. Syst. 213 (2024) 103794.

[65] Z. Rimma, T. Marina, R. Olga, C. Andrey, S. Albina, Major trends in the digital transformation of agriculture. New Silk Road: Business Cooperation and Prospective of Economic Development"(NSRBCPED 2019), Atlantis Press, 2020, pp. 271–275. Accessed: Apr. 18, 2024. [Online]Available: https://www.atlantis-press.com/proceedings/nsrbcped-19/125937906.

[66] M.-A. Jouanjean, "Digital opportunities for trade in the agriculture and food sectors," 2019, Accessed: Apr. 18, 2024. [Online]. Available: https://www.oecd-ilibrary.org/content/paper/91c40e07-en.

[67] T. Soma, B. Nuckchady, Communicating the benefits and risks of digital agriculture technologies: perspectives on the future of digital agricultural education and training, Front. Commun. 6 (2021) 762201.

[68] N. Peladarinos, D. Piromalis, V. Cheimaras, E. Tserepas, R.A. Munteanu, P. Papageorgas, Enhancing smart agriculture by implementing digital twins: a comprehensive review, Sensors 23 (16) (2023) 7128.

[69] G. Quargnali, "Hyperautomation–intelligent automation," 2022, Accessed: Apr. 18, 2024. [Online]. Available: https://www.theseus.fi/handle/10024/751688.

[70] P.W. Phillips, J.-A. Relf-Eckstein, G. Jobe, B. Wixted, Configuring the new digital landscape in western Canadian agriculture, NJAS-Wagening. J. Life Sci. 90 (2019) 100295.

[71] B. Sobirov, S. Yekimov, A. Sitkovska, L. Iushchenko, R. Dmytrenko, R. Polyakov, Using digital ecosystems in agriculture, in: Ecosystems Without Borders, 474, Springer International Publishing, Cham, 2022, pp. 171–176, https://doi.org/10.1007/978-3-031-05778-6_18, in Lecture Notes in Networks and Systems, vol. 474.

[72] E. Kashina, et al., Impact of digital farming on sustainable development and planning in agriculture and increasing the competitiveness of the agricultural business, Int. J. Sustain. Dev. Plan. 17 (8) (2022). Accessed: Apr. 18, 2024. [Online]Available: https://search.ebscohost.com/login.aspx?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=17437601&AN=161805730&h=d%2BpQW43Kh%2F8BTrF3x1vSMNWWZHM20i7fzIgeeU2pMIXvokitaqbEYxcn7OBQyjotnYHk1ElZLHmBm9QnE9tEbg%3D%3D&crl=c.

[73] J. Schuster, Big data ethics and the digital age of agriculture, Resour. Mag. 24 (1) (2017) 20–21.

[74] J.A. López-Morales, J.A. Martínez, A.F. Skarmeta, Digital transformation of agriculture through the use of an interoperable platform, Sensors 20 (4) (2020) 1153.

[75] R.K. Goel, C.S. Yadav, S. Vishnoi, R. Rastogi, Smart agriculture–urgent need of the day in developing countries, Sustain. Comput. Inform. Syst. 30 (2021) 100512.

[76] K. Rijswijk, et al., Digital transformation of agriculture and rural areas: a socio-cyber-physical system framework to support responsibilisation, J. Rural Stud. 85 (2021) 79–90.

[77] J. McFadden, E. Njuki, and T. Griffin, "Precision agriculture in the digital era: recent adoption on US farms," 2023, Accessed: Apr. 18, 2024. [Online]. Available: https://ageconsearch.umn.edu/record/333550/.

[78] T. Qin, L. Wang, Y. Zhou, L. Guo, G. Jiang, L. Zhang, Digital technology-and-services-driven sustainable transformation of agriculture: cases of China and the EU, Agriculture 12 (2) (2022) 297.

[79] P. Tripodi, N. Nicastro, C. Pane, D. Cammarano, Digital applications and artificial intelligence in agriculture toward next-generation plant phenotyping, Crop Pasture Sci. (2022). Accessed: Apr. 18, 2024. [Online]Available: https://www.publish.csiro.au/cp/cp21387.

[80] N. Khan, R.L. Ray, G.R. Sargani, M. Ihtisham, M. Khayyam, S. Ismail, Current progress and future prospects of agriculture technology: gateway to sustainable agriculture, Sustainability 13 (9) (2021) 4883.

[81] J. Ding, C. Zhang, D. Li, A.K. Sangaiah, Hyperautomation for air quality evaluations: a perspective of evidential three-way decision-making, Cogn. Comput. (2023), https://doi.org/10.1007/s12559-022-10101-8. Jan.

[82] P.B. Akmarov, O.P. Knyazeva, E.S. Tretyakova, Assessing the potential of the digital economy in agriculture, in: Proceedings of the IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2021 042036. Accessed: Apr. 18, 2024. [Online]Available: https://iopscience.iop.org/article/10.1088/1755-1315/666/4/042036/meta.

[83] A.M. Ciruela-Lorenzo, A.R. Del-Aguila-Obra, A. Padilla-Meléndez, J.J. Plaza-Angulo, Digitalization of agri-cooperatives in the smart agriculture context. proposal of a digital diagnosis tool, Sustainability 12 (4) (2020) 1325.

[84] A. Ulezko, V. Reimer, O. Ulezko, Theoretical and methodological aspects of digitalization in agriculture, in: Proceedings of the IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2019 012062. Accessed: Apr. 18, 2024. [Online]Available: https://iopscience.iop.org/article/10.1088/1755-1315/274/1/012062/meta.

[85] M. Anshari, M.N. Almunawar, M. Masri, M. Hamdan, Digital marketplace and FinTech to support agriculture sustainability, Energy Procedia 156 (2019) 234–238.

[86] A.B. Potgieter, et al., Evolution and application of digital technologies to predict crop type and crop phenology in agriculture, Silico Plants 3 (1) (2021) diab017.

[87] R.R. Shamshiri et al., "Research and development in agricultural robotics: a perspective of digital farming," 2018, Accessed: Apr. 18, 2024. [Online]. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2595468.

[88] A. Salam and U. Karabiyik, "A cooperative overlay approach at the physical layer of cognitive radio for digital agriculture," 2019, Accessed: Apr. 18, 2024. [Online]. Available: https://docs.lib.purdue.edu/cit_articles/16/.

[89] G.C. Lima, F.L. Figueiredo, A.E. Barbieri, J. Seki, Agro 4.0: enabling agriculture digital transformation through IoT, Rev. Ciênc. Agronômica 51 (2021) e20207771.

[90] E.D. Lioutas, C. Charatsari, M. De Rosa, Digitalization of agriculture: a way to solve the food problem or a trolley dilemma? Technol. Soc. 67 (2021) 101744.

[91] J. Clapp, S.-L. Ruder, Precision technologies for agriculture: digital farming, gene-edited crops, and the politics of sustainability, Glob. Environ. Polit. 20 (3) (2020) 49–69.

[92] A. Zhang, I. Baker, E. Jakku, and R. Llewellyn, "Accelerating precision agriculture to decision agriculture: the needs and drivers for the present and future of digital agriculture in Australia," 2017, Accessed: Apr. 18, 2024. [Online]. Available: https://elibrary.sugarresearch.com.au/handle/11079/16480.

[93] M.A. Dayıoğlu, U. Turker, Digital transformation for sustainable future-agriculture 4.0: a review, J. Agric. Sci. 27 (4) (2021) 373–399.

[94] A. Sridhar, A. Balakrishnan, M.M. Jacob, M. Sillanpää, N. Dayanandan, Global impact of COVID-19 on agriculture: role of sustainable agriculture and digital farming, Environ. Sci. Pollut. Res. 30 (15) (2022) 42509–42525, https://doi.org/10.1007/s11356-022-19358-w. Mar.

[95] L. Yong, L. Xiushan, Z. Degui, L. Fu, The main content, technical support and enforcement strategy of digital agriculture, Geo-Spat. Inf. Sci. 5 (1) (2002) 68–73, https://doi.org/10.1007/BF02863497. Jan.

[96] D.S. Gangwar, S. Tyagi, S.K. Soni, A techno-economic analysis of digital agriculture services: an ecological approach toward green growth, Int. J. Environ. Sci. Technol. 19 (5) (2022) 3859–3870, https://doi.org/10.1007/s13762-021-03300-7. May.

[97] I.L. Vorotnikov, N.V. Ukolova, S.V. Monakhov, J.A. Shikhanova, and V.V. Neyfeld, "Economic aspects of the development of the" digital agriculture" system.," 2020, Accessed: Apr. 18, 2024. [Online]. Available: https://managementjournal.usamv.ro/pdf/vol.20_1/Art78.pdf.

[98] G.E. Mushi, G. Di Marzo Serugendo, P.-Y. Burgi, Digital technology and services for sustainable agriculture in Tanzania: a literature review, Sustainability 14 (4) (2022) 2415.

[99] A. Kayad, M. Sozzi, S. Gatto, B. Whelan, L. Sartori, F. Marinello, Ten years of corn yield dynamics at field scale under digital agriculture solutions: a case study from North Italy, Comput. Electron. Agric. 185 (2021) 106126.

[100] Y. Edan, G. Adamides, R. Oberti, Agriculture automation, in: S.Y. Nof (Ed.), Springer Handbook of Automation, Springer International Publishing, Cham, 2023, pp. 1055–1078, https://doi.org/10.1007/978-3-030-96729-1_49, in Springer Handbooks.

[101] K. Bronson, I. Knezevic, Big data in food and agriculture, Big Data Soc. 3 (1) (2016), https://doi.org/10.1177/2053951716648174, 205395171664817Jun.

[102] D.D. Burra et al., "Digital agriculture profile: Vietnam," 2021, Accessed: Apr. 18, 2024. [Online]. Available: https://cgspace.cgiar.org/items/77524a19-14ea-47c5-ba03-4f5d44d449ed.

[103] R. Fabregas, M. Kremer, F. Schilbach, Realizing the potential of digital development: the case of agricultural advice, Science 366 (6471) (2019) eaay3038, https://doi.org/10.1126/science.aay3038. Dec.

[104] E. Jakku, A. Fleming, M. Espig, S. Fielke, S.C. Finlay-Smits, J.A. Turner, Disruption disrupted? Reflecting on the relationship between responsible innovation and digital agriculture research and development at multiple levels in Australia and Aotearoa New Zealand, Agric. Syst. 204 (2023) 103555.

[105] A.-R. Abdulai, A new Green Revolution (GR) or neoliberal entrenchment in agri-food systems? Exploring narratives around digital agriculture (da), food systems, and development in Sub-Sahara Africa, J. Dev. Stud. 58 (8) (2022) 1588–1604, https://doi.org/10.1080/00220388.2022.2032673. Aug.

[106] A. Scuderi, G.La Via, G. Timpanaro, L. Sturiale, The digital applications of 'Agriculture 4.0': strategic opportunity for the development of the Italian citrus chain, Agriculture 12 (3) (2022) 400.

[107] D. Yane, D. Li, Y. Liu, Y. Chen, Research and analysis about system of digital agriculture based on a network platform, in: Computer and Computing Technologies in Agriculture IV, 345, Springer Berlin Heidelberg, Berlin, Heidelberg, 2011, pp. 274–282, https://doi.org/10.1007/978-3-642-18336-2_33, in IFIP Advances in Information and Communication Technology, vol. 345.

[108] M. Awais, et al., UAV-based remote sensing in plant stress imagine using high-resolution thermal sensor for digital agriculture practices: a meta-review, Int. J. Environ. Sci. Technol. 20 (1) (2023) 1135–1152, https://doi.org/10.1007/s13762-021-03801-5. Jan.

[109] W. Zhang, Study about IOT's application in" digital Agriculture" construction, in: Proceedings of the International Conference on Electrical and Control Engineering, IEEE, 2011, pp. 2578–2581. Accessed: Apr. 18, 2024. [Online] Available: https://ieeexplore.ieee.org/abstract/document/6057405/.

[110] A. Salam, "A path loss model for through the soil wireless communications in digital agriculture," 2019, Accessed: Apr. 18, 2024. [Online]. Available: https://docs.lib.purdue.edu/cit_articles/18/.

[111] S. Himesh, et al., Digital revolution and Big Data: a new revolution in agriculture, CABI Rev. (2018) 1–7, https://doi.org/10.1079/PAVSNNR201813021. Aug.

[112] H. Van Es, J. Woodard, Innovation in agriculture and food systems in the digital age, Glob. Innov. Index 99 (2017). Accessed: Apr. 18, 2024. [Online]Available: https://www.researchgate.net/profile/Kupeshova-Saule/publication/325777714_Problems_of_developing_the_foundations_of_sustainable_competitiveness_of_industrial_and_innovative_economy_in_Kazakhstan/links/601cfea2299bf1cc26a2f80d/Problems-of-developing-the-foundations-of-sustainable-competitiveness-of-industrial-and-innovative-economy-in-Kazakhstan.pdf?origin=journalDetail&_tp=eyJwYWdlIjoiam91cm5hbERldGFpbCJ9#page=127.

[113] J. Liu, P. Sengers, Legibility and the legacy of racialized dispossession in digital agriculture, Proc. ACM Hum.-Comput. Interact. 5 (CSCW2) (2021) 1–21, https://doi.org/10.1145/3479867. Oct.

[114] A.N. Alahmadi, S.U. Rehman, H.S. Alhazmi, D.G. Glynn, H. Shoaib, P. Solé, Cyber-security threats and side-channel attacks for digital agriculture, Sensors 22 (9) (2022) 3520.

[115] S. Cook, E.L. Jackson, M.J. Fisher, D. Baker, D. Diepeveen, Embedding digital agriculture into sustainable Australian food systems: pathways and pitfalls to value creation, Int. J. Agric. Sustain. 20 (3) (2022) 346–367, https://doi.org/10.1080/14735903.2021.1937881. May.

[116] P.P. Jayaraman, D. Palmer, A. Zaslavsky, D. Georgakopoulos, Do-it-yourself digital agriculture applications with semantically enhanced IoT platform, in: Proceedings of the IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks And Information Processing (ISSNIP), IEEE, 2015, pp. 1–6. Accessed: Apr. 17, 2024. [Online]Available: https://ieeexplore.ieee.org/abstract/document/7106951/.

[117] V. Romanov, I. Galelyuka, H. Antonova, O. Kovyrova, V. Hrusha, O. Voronenko, Application of wireless sensor networks for digital agriculture, in: Proceedings of the 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), IEEE, 2019, pp. 340–344. Accessed: Apr. 18, 2024. [Online]Available: https://ieeexplore.ieee.org/abstract/document/8924267/.

[118] L. Hrustek, Sustainability driven by agriculture through digital transformation, Sustainability 12 (20) (2020) 8596.

[119] C. Pylianidis, S. Osinga, I.N. Athanasiadis, Introducing digital twins to agriculture, Comput. Electron. Agric. 184 (2021) 105942.

[120] P.J. Sarkar, S. Chanagala, A survey on IOT based digital agriculture monitoring system and their impact on optimal utilization of resources, J. Electron. Commun. Eng. IOSR-JECE 11 (1) (2016) 1–4.

[121] A.K. Subaeva, M.M. Nizamutdinov, L.M. Mavlieva, Changes of the agricultural staff potential in the transition to digital agriculture. BIO Web of Conferences, EDP Sciences, 2020, p. 00178. Accessed: Apr. 18, 2024. [Online]Available: https://www.bio-conferences.org/articles/bioconf/abs/2020/01/bioconf_fies2020_00178/bioconf_fies2020_00178.html.

[122] S. Rolandi, G. Brunori, M. Bacco, I. Scotti, The digitalization of agriculture and rural areas: towards a taxonomy of the impacts, Sustainability 13 (9) (2021) 5172.

[123] E.A. Skvortsov, E.G. Skvortsova, I.S. Sandu, G.A. Iovlev, Transition of agriculture to digital, intellectual and robotics technologies, Ekon. Reg. Econ. Reg. (3) (2018) 1014.

[124] A. Nasirahmadi, O. Hensel, Toward the next generation of digitalization in agriculture based on digital twin paradigm, Sensors 22 (2) (2022) 498.

[125] R. Dara, S.M. Hazrati Fard, J. Kaur, Recommendations for ethical and responsible use of artificial intelligence in digital agriculture, Front. Artif. Intell. 5 (2022) 884192.

[126] V.S. Osipov, A.V. Bogoviz, Transition to digital agriculture: background, road map, possible consequences, Econ. Agric. Russ. (2017).

[127] T. Grift, Q. Zhang, N. Kondo, K.C. Ting, A review of automation and robotics for the bio-industry, J. Biomechatr. Eng. 1 (1) (2008) 37–54.

[128] A. Subeesh, C.R. Mehta, Automation and digitization of agriculture using artificial intelligence and internet of things, Artif. Intell. Agric. 5 (2021) 278–291.

[129] S. Madakam, R.M. Holmukhe, R.K. Revulagadda, The next generation intelligent automation: hyperautomation, JISTEM-J. Inf. Syst. Technol. Manag. 19 (2022) e202219009.

[130] K. Parasuraman, U. Anandan, A. Anbarasan, IoT based smart agriculture automation in artificial intelligence, in: Proceedings of the Third International Conference on Intelligent Communication Technologies and Virtual Mobile Networks (ICICV), IEEE, 2021, pp. 420–427. Accessed: Apr. 18, 2024. [Online] Available: https://ieeexplore.ieee.org/abstract/document/9388578/.

[131] D. Mehta, P. Gupta, A.K. Upadhyay, Transferring the modeling capabilities of hyper spectral image analysis to agricultural automation, in: Proceedings of the International Conference on Optimization Computing and Wireless Communication (ICOCWC), IEEE, 2024, pp. 1–7. Accessed: Apr. 18, 2024. [Online]Available: https://ieeexplore.ieee.org/abstract/document/10470536/.

[132] S. Chaterji et al., "Artificial intelligence for digital agriculture at scale: techniques, policies, and challenges." arXiv, Jan. 21, 2020. Accessed: Apr. 17, 2024. [Online]. Available: http://arxiv.org/abs/2001.09786.

[133] A. Walter, R. Finger, R. Huber, N. Buchmann, Smart farming is key to developing sustainable agriculture, Proc. Natl. Acad. Sci. 114 (24) (Jun. 2017) 6148–6150, https://doi.org/10.1073/pnas.1707462114.

[134] E.M. Musiu, L. Qi, Y. Wu, Spray deposition and distribution on the targets and losses to the ground as affected by application volume rate, airflow rate and target position, Crop Prot. 116 (2019) 170–180.

[135] T. Utstumo, et al., Robotic in-row weed control in vegetables, Comput. Electron. Agric. 154 (2018) 36–45.

[136] D. Sarri, L. Martelloni, M. Vieri, Development of a prototype of telemetry system for monitoring the spraying operation in vineyards, Comput. Electron. Agric. 142 (2017) 248–259.

[137] M. Grella, P. Marucco, M. Manzone, M. Gallart, P. Balsari, Effect of sprayer settings on spray drift during pesticide application in poplar plantations (Populus spp, Sci. Total Environ. 578 (2017) 427–439.

[138] K.A. Vakilian, J. Massah, A farmer-assistant robot for nitrogen fertilizing management of greenhouse crops, Comput. Electron. Agric. 139 (2017) 153–163.

[139] A. Malneršič, M. Dular, B. Širok, R. Oberti, M. Hočevar, Close-range air-assisted precision spot-spraying for robotic applications: aerodynamics and spray coverage analysis, Biosyst. Eng. 146 (2016) 216–226.

[140] M. Gonzalez-de-Soto, L. Emmi, M. Perez-Ruiz, J. Aguera, P. Gonzalez-de-Santos, Autonomous systems for precise spraying–evaluation of a robotised patch sprayer, Biosyst. Eng. 146 (2016) 165–182.

[141] J. Cashbaugh, S. Bradley, Evaluation of a spray scheduling system, IFAC-Pap. 49 (16) (2016) 226–230.

[142] R. Oberti, et al., Selective spraying of grapevines for disease control using a modular agricultural robot, Biosyst. Eng. 146 (2016) 203–215.

[143] G. Kennedy, V. Ila, R. Mahony, A perception pipeline for robotic harvesting of green asparagus, IFAC-Pap. 52 (30) (2019) 288–293.

[144] J.J. Zhuang, S.M. Luo, C.J. Hou, Y. Tang, Y. He, X.Y. Xue, Detection of orchard citrus fruits using a monocular machine vision-based method for automatic fruit picking applications, Comput. Electron. Agric. 152 (2018) 64–73.

[145] Z.J. Zhuang JiaJun et al., "Computer vision-based localisation of picking points for automatic litchi harvesting applications towards natural scenarios.," 2019, Accessed: Apr. 18, 2024. [Online]. Available: https://www.cabidigitallibrary.org/doi/full/10.5555/20193491767.

[146] X. Ling, Y. Zhao, L. Gong, C. Liu, T. Wang, Dual-arm cooperation and implementing for robotic harvesting tomato using binocular vision, Robot. Auton. Syst. 114 (2019) 134–143.

[147] S. Gutiérrez, A. Wendel, J. Underwood, Spectral filter design based on in-field hyperspectral imaging and machine learning for mango ripeness estimation, Comput. Electron. Agric. 164 (2019) 104890.

[148] H. Abd-El Monsef, S.E. Smith, D.L. Rowland, N.Abd El Rasol, Using multispectral imagery to extract a pure spectral canopy signature for predicting peanut maturity, Comput. Electron. Agric. 162 (2019) 561–572.

[149] J. Gené-Mola, et al., Fruit detection in an apple orchard using a mobile terrestrial laser scanner, Biosyst. Eng. 187 (2019) 171–184.

[150] N.Z. Nurazwin Zulkifli, N.H. Norhashila Hashim, K.A. Khalina Abdan, and M.H. Marsyita Hanafi, "Application of laser-induced backscattering imaging for predicting and classifying ripening stages of" Berangan" bananas.," 2019, Accessed: Apr. 18, 2024. [Online]. Available: https://www.cabidigitallibrary.org/doi/full/10.5555/20193430602.

[151] Y. Xiong, C. Peng, L. Grimstad, P.J. From, V. Isler, Development and field evaluation of a strawberry harvesting robot with a cable-driven gripper, Comput. Electron. Agric. 157 (2019) 392–402.

[152] L.Z. Li ZhiGuo, M.F. Miao FengLi, Y.Z. Yang ZhiBo, and W.H. Wang HongQiang, "An anthropometric study for the anthropomorphic design of tomato-harvesting robots.," 2019, Accessed: Apr. 18, 2024. [Online]. Available: https://www.cabidigitallibrary.org/doi/full/10.5555/20193430785.

[153] Z.B. Zhang BaoHua et al., "Comparative study of mechanical damage caused by a two-finger tomato gripper with different robotic grasping patterns for harvesting robots.," 2018, Accessed: Apr. 18, 2024. [Online]. Available: https://www.cabidigitallibrary.org/doi/full/10.5555/20183351907.

[154] L. Mu, G. Cui, Y. Liu, Y. Cui, L. Fu, Y. Gejima, Design and simulation of an integrated end-effector for picking kiwifruit by robot, Inf. Process. Agric. 7 (1) (2020) 58–71.

[155] R. Barth, J. Hemming, E.J. Van Henten, Angle estimation between plant parts for grasp optimisation in harvest robots, Biosyst. Eng. 183 (2019) 26–46.

[156] Y. Wang, et al., End-effector with a bite mode for harvesting citrus fruit in random stalk orientation environment, Comput. Electron. Agric. 157 (2019) 454–470.

[157] A. Roshanianfard, N. Noguchi, Characterization of pumpkin for a harvesting robot, IFAC-Pap. 51 (17) (2018) 23–30.