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Review: unmanned aerial vehicles and artificial intelligence in precision agriculture

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Abstract. To meet the needs of sustainable intensification in crop and animal production, farmers use a set of technologies which are referred to as Agriculture 4.0 to 5.0 or digital agriculture. Differences compared to traditional precision farming techniques are in extensive use of UAV, smart sensors implemented in machines, crops, animals and in the soil, cloud computing, IoT, together with extensive use of AI for data analyses. Unmanned Aerial Vehicles (UAV), also called drones, have become an essential tool in digital agriculture. UAVs have witnessed remarkable development in the past decades and so in the recent years, the topic of agricultural UAVs has gained the attention of many farmers. The submitted paper provides a review on recent scientific literature dedicated to the utilization of agricultural UAVs. The utilization areas are reviewed in monitoring (remote sensing), interventional applications of various inputs, and other areas of possible utilization. The novelty of this review highlights the importance of the integration of UAVs with artificial intelligence (AI) and the Internet of Things (IoT). Sophisticated artificial intelligence and machine-learning algorithms are developing to analyse UAV-collected data, enhancing the accuracy and efficiency. Machine learning models in combination with artificial intelligence are capable of yield prediction and crop management, effecting future decision-making processes. Several key opportunities can be identified for future research, including the development of more sophisticated decision-making processes and machine learning methods based on artificial intelligence, the automation of agricultural crop production, improved UAV autonomy, and the potential use of UAV swarms in different field operations.

Key words: artificial intelligence, drone; precision agriculture, unmanned aerial vehicle, unmanned aerial spraying system.

INTRODUCTION

The agricultural sector worldwide is facing many challenges, including climate change, social and economic changes, which threaten the food production and food security (Inoue, 2020). The world population is estimated to reach about 10 billion by 2050, affecting the food consumption globally (United Nations, 2024). Furthermore, the total arable-land area is decreasing worldwide due to climate change, desertification, floods and increasing built-up area. Thus, sustainable resource management is crucial to overcome these challenges. To address these challenges, modern farming approaches were developed based on technological advancements.

At first, the allowance of the global positioning systems (GPS) in 1983 for civilian use led to the beginning of precision agriculture in 1992. It was a major step forward due to the ability of the GPS system to geolocate the information about soil and crops. Precision agriculture started the technological revolution of Agriculture 4.0. Precision agriculture is primarily a data-driven approach and is undergoing remarkable changes due to unmanned aerial vehicles (UAV) and their ability to acquire vast amounts of data quickly and efficiently. The hypothesis behind precision agriculture is that each field is not uniform, and both soil and crops have their site-specific needs. The International Society of Precision Agriculture defines precision agriculture as 'a management strategy that gathers, processes and analyses temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production' (Lowenberg-DeBoer & Erickson, 2019; Balafoutis et al., 2020; Ammoniaci et al., 2021; ISPA, 2024; Guebsi et al., 2024; Singh et al., 2024).

Later, smart farming techniques, as an advancement of precision agriculture dealing with the application of information technologies and efficient decision-making processes based on the collected data, has been adopted (Iqbal, 2024). According to the International Organization for Standardization (ISO), smart farming is a data-driven, principled decision-making approach using information communication technology and data analytics in agriculture (ISO, 2023). However, huge development and innovation processes in agriculture indicate the rise of the new technological revolution - Agriculture 5.0, also referred to as 'Digital Agriculture'. Agriculture 5.0 aims to apply information and communication-based technologies (ICT) introduced in Agriculture 4.0 with the focus on Internet of Things (IoT), Unmanned Aerial Vehicles (UAV), Artificial Intelligence (AI) technology, machine learning and deep learning. Digital agriculture can be defined as a combination of two modern farming approaches, i.e. precision agriculture (precision farming) and smart farming. However, in literature, these terms are often being used interchangeably (Javaid et al., 2022; Ragazou et al., 2022; Iqbal, 2024). With the arrival of new technologies within Agriculture 5.0 further streamlining of decision-making processes is expected, bringing fundamental changes in the management and production processes. Multi-criterial decision-making process, which must include adequate reaction to frequent changes in production (climate factors, pests and disease occurrence, uneven distribution of rainfalls) will be possible to realize without human intervention.

Nowadays, the development and implementation of UAV and AI technology plays a crucial role in the innovation processes. This development over the past 5 years had a great acceleration, which brings the importance to be able to orientate in this field of interest and recent trends. Although the current agricultural sector is on the interface of technological revolutions of Agriculture 4.0 and Agriculture 5.0, different levels of revolutions are in practise worldwide, depending on the geographical locations (Iqbal, 2024).

Review Aim

The aim of this review was to point out the future trends and importance of linking the technology of UAV with AI as one of the basic tools of the latest technological revolution Agriculture 5.0. This literature review focused on the utilization of UAV and AI in agriculture crop and animal production. The aim of this review was to provide an up-to-date report on UAV and AI applications in crop and animal production with a critical review of their use in practical farming, as well as research. The information compiled in this paper should identify the existing research needs and promising future research areas.

UNMANNED AERIAL VEHICLES

Unmanned aerial vehicles (UAV) are commonly known as drones or unmanned aircrafts. According to the European Union Aviation Safety Agency (EASA), a UAV can be defined as any aircraft operating or designed to operate autonomously or to be piloted remotely without a pilot (operator) on board. Commonly, the trajectory of flight (UAV flight mission) is predefined, although it can be controlled by an operator (pilot) through remote teleoperation commands from a ground station, affecting its motion and direction. Other terms are also used in UAV terminology, i.e. unmanned aircraft system (UAS) referring to a drone, its system, and all the other equipment used to control and operate it, and remotely piloted aircraft system (RPAS), which is a subcategory of UAS. (Radoglou-Grammatikis et al., 2020; EASA, 2024).

The variety of present UAVs is enormous - varying in characteristics such as size, flight, endurance, capabilities; construction type; specifications or flexibility. Classification of UAVs can be based on aerodynamics features, level of autonomy, size and weight, power source or maximum payload. From the technical and construction type point of view, classification based on aerodynamics features is commonly applied, dividing UAVs into fixed-wing, rotary-wing and hybrid types (Radoglou-Grammatikis et al., 2020; Mohsan et al., 2023; Toscano et al., 2024). According to the construction type, UAVs can be classified as:

Fixed-wing UAVs – These are characterized by the presence of stationary airfoil-shaped wings that generate lift, enabling the aircraft to take off from the ground. The control of fixed-wing UAV is accomplished through elevators, ailerons and rudder that are attached to the wings. These construction characteristics enable UAVs to turn around roll, pitch and yaw angles. Fixed-wing UAVs are operated in higher altitudes, able to cover lager areas, which makes them suitable for large-scale mapping and surveillance missions. However, the operation of this type of UAV requires a skilled pilot, proper training, and suitable take-off and landing areas. Foldable-wing UAVs enhance the portability while maintaining performance comparable to fixed-wing UAVs (Radoglou-Grammatikis et al., 2020; Toscano et al., 2024; Guebsi et al., 2024).

Rotary-wing UAVs – These are composed of one/several rotor/s that generate the appropriate power necessary for lifting. This type does not need a forward airspeed for lifting (unlike fixed-wing UAVs) and is capable of hovering. Rotary-wing UAVs are divided into single rotor-types or multi-rotor types. A single-rotor UAV type (often referred to as helicopter or helicopter-type UAV) features a single set of blades connected to a central shaft, which rotates at a specific speed. However, the manoeuvrability and operation of single-rotor UAVs requires more proper training and skilled operator. A multi-rotor UAV consists of sets of rotors with blades attached, varying from two to eight and more rotors. Depending on the number of rotors, multi-rotor UAVs can be classified into subcategories, e.g. bicopters, tricopters, quadcopters, hexacopters or octocopters. Rotary-wing UAVs are better and easier to control and are capable to carry a heavier payload compared to the fixed-wing type. They can be implemented in more precise and site-specific operations (Radoglou-Grammatikis et al., 2020; Guebsi et al., 2024; Toscano et al., 2024).

Hybrid UAVs – The term hybrid in this context refers to UAVs that combine the features of both fixed-wing and rotary-wing UAVs. Hybrid UAVs possesses rotors for vertical take-off and landing but also include fixed-wings utilised for covering large areas in mapping operations (Radoglou-Grammatikis et al., 2020; Guebsi et al., 2024).

At present, UAVs are being used in multiple applications including military, industrial, research, commercial and civil applications. Furthermore, they are being applied in transportation operations, safety and surveillance missions, search and rescue, etc. As part of the industrial applications, remote sensing operations and precision agriculture operations are involved (Mohsan et al., 2023).

The rise of digital technologies and advanced sensors in the early 2000s led to a broader utilization of UAVs in agriculture. UAVs are highly capable to conduct various tasks in the agricultural sector across multiple areas including remote sensing operations (variability determination, growth assessment, weed detection etc.), mapping, spraying applications (fertilizers and pesticides), fertilizer spreading, seed sowing, transporting certain goods etc. As (Fig. 1) shows, UAV utilization areas can be classified to three categories to which the greatest attention is given, following the UAV monitoring (remote sensing operations), interventional applications and other areasof utilization (Jeongeun et al., 2019; Aslan et al., 2022; Singh et al., 2024).

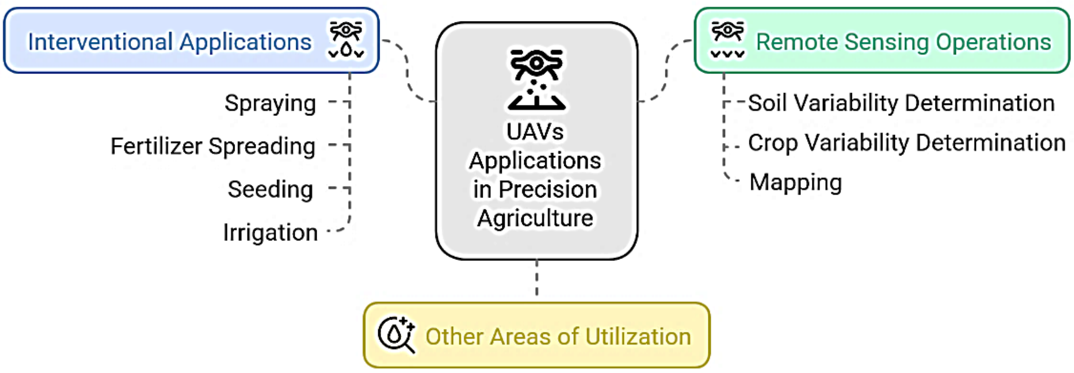

Figure 1. Classification of UAV utilization areas in precision agriculture.

Remote sensing operations

In remote sensing UAV operations, the sensing altitude is crucial. An UAV is included in an aerial monitoring platform, however in terms of sensing, it is on the interface of proximal and remote sensing, as (Fig. 2) shows. Lower operating altitude of the UAV enables to acquire data from shorter distance above the surface of soil/crop similarly to ground-based proximal sensing platforms. It provides images with finer spatial resolution suitable for precise sensing (e.g. plant counting), whereas higher operating altitude is suitable for bigger scale sensing or mapping with lower spatial resolution covering larger areas and increasing the efficiency of sensing.

Sensors utilized in remote sensing operations are passive or active and are exchangeable (dismountable) or built-in parts of different platforms in remote sensing. Passive sensors use natural source of light (primarily Sun) to measure the electromagnetic energy reflected from the Earth surface, whereas active sensors provide their own form of illumination. Examples of the sensors include (Žížala et al., 2021; NASA, 2025) passive sensors (Red Green Blue (RGB), VIS (Visible), multispectral and hyperspectral, thermal) and active sensors (radio detection and ranging (radar), Light Detection and Ranging (LiDAR) and microwave-band based).

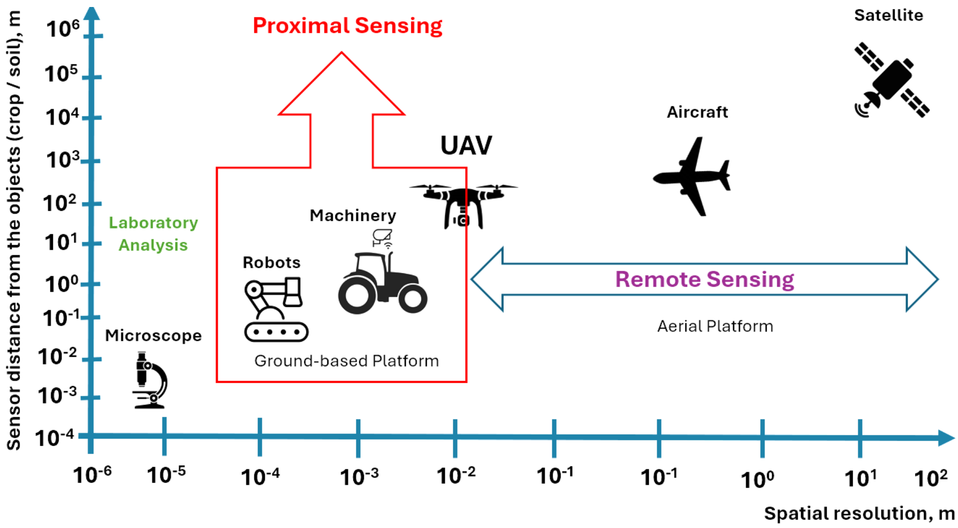

Figure 2. Monitoring platforms in precision agriculture (Modified according to Oerkle, 2019).

The main three remote sensing platforms (also referred to as mobile remote sensing platforms) include satellite-based, airborne-based (aircrafts and helicopters) and UAV-based platforms. Satellite-based platform is a higher-altitude remote sensing method, equipped with various types of sensors and capable of covering larger areas compared to UAV-based platform. However, satellite-based platforms are expensive, and for precision agriculture applications higher-detailed images (with finer resolution) and better data availability are required. These factors are leading to the utilization of UAV-based platform. As mentioned above, this platform is flexible and is capable of both lower-to-ground and higher-to-ground remote sensing with data/images available almost immediately. Image processing techniques are getting more reliable and thus increasingly adopted. The massive development in UAV technology leads to the path of automation, including automated flights and mission planning with minimal human intervention. Moreover, UAVs can be operated at much lower costs in contrast to satellites. Despite the above-mentioned benefits of UAV-based platform, the greatest drawback for their implementation among many farmers is the significantly lower territorial coverage area, flight time (ranging from 30 to 45 minutes) and the requirement for specialized personnel, i.e. trained pilots or operators (Žížala et al., 2021; Phang et al., 2023; Iqbal, 2024).

Understanding the characteristics and the variability of the cultivated soils and crops is crucial for effective crop management. UAVs are a promising technology for soil and crop monitoring due to their versatility of various utilized sensors. For soil monitoring, ground based platforms of proximal sensing are more frequently used nowadays, however, some results were published recently aimed at soil-water regimes and environmental indicators as GHG emissions. Crop monitoring via UAVs typically employs high-resolution imaging techniques aimed at defining vegetation indices and quantitative indicators enabling the monitoring of crop conditions, as well as pests, diseases and weeds. These techniques provide valuable information on parameters such as growth, biomass content, vitality, health status, stress or water content (Toscano et al., 2024). Recently published results in the area of remote sensing operations are summarized in Table 1.

It is evident from Table 1, that almost all indicators of the soil and crop status can be monitored with sensors carried by UAVs. The biggest potential can be seen in areas where a rapid and agile action needs to be done after the soil/crop monitoring as e.g. in the case of pests/disease and weed infection. As for pests and disease, the key role is to identify, characterize and geo-locate the detected irregularities, but also the disease status or level of pest infestation. As Table 1 shows, various sensor can be used for pests and disease identification. Such sensors include (Aslan et al., 2022; Guebsi et al., 2024; Toscano et al., 2024) RGB, VIS, multispectral and hyperspectral sensors. RGB sensors are capable of detection of damaged or infested areas. However, multispectral and hyperspectral sensors are proven to be more efficient and versatile. They are capable of more detailed plant health assessment and early disease detection.

The weed detection process is based on the principle of 'green on brown' or 'green on green'. The 'green on brown' principle identifies the weeds mostly in the pre-sowing process (getting rid of weeds prior to planting), at the early growing stage of primary cultivated crop or after the harvest. The 'green on green' principle identifies the weeds in the early and late growing phase of primary cultivated crop. This principle is more difficult for weed identification. To achieve relevant results, it cooperates with AI, which helps to analyse individual plants and detect features such as colour or shape differences (Kool et al., 2023; Mahmudul Hasan, 2024; Cultiwise, 2025).

Novelty in agricultural application can be seen in UAVs equipped with LiDAR sensors. These are a promising tool for the estimation of biomass and crop structure and crop/tree canopy estimation. Furthermore, LiDAR sensors are included in highly detailed 3D terrain modelling operations. Combining LiDAR data with precise georeferencing techniques allows for the creation of high-resolution soil maps. By analysing variations in surface elevation and slopes, different soil types can be identified, classified and mapped, and their spatial distribution within a field. Such maps provide farmers with valuable data on elevation and spatial distribution of soil surface roughness. Valuable data from mapping also have a potential in validating soil erosion models. Furthermore, high potential of UAVs can be seen in soil surface roughness measurements and estimation using the technology of both LiDAR and Photogrammetry (Alexiou et al., 2022; Farhan et al., 2024; Guebsi et al., 2024).

Table 1. Overview of published results on monitoring (remote sensing) using different sensors carried by UAVs

UAV operation	Property determined	Recent studies	Sensor Type and Analysis Method
Soil variability determination	Soil moisture	Zhang J. et al. (2025)	Multispectral and infrared sensor
	Soil salinity	Zhao et al. (2023)	Multispectral sensor and image texture
	GHG emissions from soil	Fosco et al. (2024)	Special sensor capable to detect and quantify the emissions
	Soil organic matter	Zhou J. et al. (2023)	Multispectral sensor imagery and machine learning algorithm
UAV operation	Property determined	Recent Studies	Sensor Type and Analysis Method
Crop variability determination	Crop emergence	Li et al. (2019)	RGB sensor and semi-automated image analysis software
	Crop classification	Deng et al. (2024)	Multispectral images with object-oriented method and random forest algorithm for crop identification using multispectral UAV images
	Plant counting	Sun H. et al. (2025)	High resolution RGB sensor with lightweight model (P2P-CNF)
	Crop yield estimation	García-Martínez et al. (2020)	Neural network using multispectral and RGB images
		Lukas et al. (2022)	Multispectral imagery and estimation of vegetation indices
	Tree canopy estimation	Cantón-Martínez et al. (2024)	LiDAR sensor and statistical analysis between LiDAR and field measurements
	Water stress detection	Yunhyeok et al. (2021)	Thermal sensor imagery used for further processing
	Nutrient content deficiency	Yu et al. (2023)	Hyperspectral sensor data and machine learning
		Shu et al. (2024)	Multispectral sensor
	Pests and disease identification	Shah et al. (2023)	High-resolution RGB sensor and deep learning algorithm
		Guan et al. (2024)	High-resolution RGB sensor
		Zhang X. et al. (2019)	Hyperspectral imagery and deep learning approach
	Weed identification	Pei et al. (2022)	High-resolution RGB sensor and YOLOv4 weed detection model
Surface mapping	3D terrain modelling of surface, slope, elevation	Alexiou et al. (2022); Farhan et al. (2024); Guebsi et al. (2024)	LiDAR sensor
	Soil surface roughness	Onnen et al. (2020)	Photogrammetry
		Xingming et al. (2021)	LiDAR sensor

Interventional Applications

The utilization of UAVs is no longer limited to remote sensing operations in agriculture, as now they are capable of direct interventions on both crops and soils. Special UAVs are able to conduct precise interventional applications of various inputs. These applications are site-specific applications, including variable rate technology (VRT) and targeted application. Moreover, the application process of various inputs is being automatized, thus the human intervention and human exposure to the inputs are being eliminated (Chen, H. et al., 2021). Table 2 shows the uses of possible inputs for interventional applications and includes recently published studies in this area.

Table 2. Overview of published results on interventional applications of various inputs by UAVs

Input	Interventional Application	Recent Studies	Description
Pesticide	Precision spraying	Arakawa & Kamio (2023)	Application of ultra-low-volume pesticide in chestnut orchards
		Lopes et al. (2023)	Pesticide application in soybeans and evaluation of 4 different nozzle types
		Zhou Q. et al. (2023)	Pesticide application in wheat and performance evaluation of different types of UAVs
Herbicide	Precision spraying	Guo et al. (2024)	Herbicide application in rice fields including a VRT prescription map
		Pranaswi et al. (2024)	Herbicide application in wheat fields and evaluation of different spraying parameters
Insecticide	Precision spraying	Sun T. et al. (2022)	Insecticide application in wheat fields and comparison of droplet distribution under different operation parameters
		Liu et al. (2023)	Insecticide application in alfalfa fields and analysis of the impact of spraying volume on the droplet deposition
		Guan et al. (2024)	Insecticide application in rice fields including a VRT prescription map
Fertilizer (liquid)	Precision spraying	Kharim et al. (2019)	Organic liquid fertilizer application in rice fields and droplet deposition density evaluation
		Xu et al. (2023)	Chelated-zinc fertilizer application to produce zinc-biofortified rice grains
Fertilizer (solid)	Fertilizer spreading	Song et al. (2023)	Fertilizer spreading (granular urea) and analysis of particle deposition distribution of two UAVs under different operational parameters
Seed	Aerial seeding	Zhang S. et al. (2022)	Oilseed rape aerial seeding and parameters optimalization in mountainous areas
Tree seed	Aerial seeding	Castro et al. (2024)	Aerial seeding in the process of forest restoration in inaccessible terrain
Water	Irrigation	Emerging future research area	Site-specific distribution of water in smart irrigation approaches
Pollen	Artificial pollination/ UAV assisted pollination	Alyafei et al. (2022)	Artificial pollination of date palms
		Hulens et al. (2022)	Development of small UAVs capable of autonomous approach of flowers and pollination
Insects	Biological control and beneficial insects release	Martel et al. (2021)	Releasing parasitic insects against an agricultural and forest pest

It is evident from Table 2, that various inputs may be applied by UAVs. As for liquid inputs (pesticides, herbicides, fertilizers etc.), very high potential can be seen in precision spraying. Spraying is the most frequently used UAV interventional application. The popularity of such UAVs is rising mainly in Asia (Japan, China, South Korea, India), Brazil, USA, UK and a few countries of EU. UAVs equipped with spraying systems are also referred to as unmanned aerial spraying systems (UASS). Other terms such as uncrewed aerial vehicle, unmanned aerial system, and remotely piloted aerial application system (RPAAS) are also being used (Ozkan, 2024; UAPASTF, 2024). Furthermore, it is apparent from Table 2 that the recent studies also focused on the parameters of spraying, droplet deposition and evaluation of spraying nozzle types. Further research is needed to study the overall quality and safety of aerial spraying. As for water, UAVs may be used in specific scenarios for water distribution of smaller volumes in smart irrigation processes, and it might be a future emerging research area.

In case of solid inputs (seeds, solid fertilizers), potential can be seen in aerial seeding and fertilizer spreading. Aerial seeding in agriculture and forestry is among the latest possible applications of UAVs. An aerial seeding system consists of an UAV equipped with seed/plant disperse system capable of seeding/ planting, mostly used in inaccessible terrains. High potential of UAVs can be seen in forestry in the process of forest restoration. However, additional research and development is needed in this area to provide more details on the precision of the UAV aerial seeding systems (Jeongeun et al., 2019; Castro et al., 2024). As mentioned earlier, UAV fertilizer spreading technology is another promising area of possible utilization. The spreading system is similar to aerial seeding systems and is suitable for mainly granular fertilizer, both in targeted and VRT applications (Wang, X. et al., 2024; Zhou, H. et al., 2024).

As for non-ordinary inputs (pollen, insects), the novelty of UAV interventional applications can be seen in both artificial pollination and biological insects' release. However, it is important to state that artificial pollination is only an alternative solution to the decline of natural pollinators, not a replacement. Jeongeun et al. (2019) states, that the development of UAV pollinators opens new solutions, such as carrying the pollen in the animal hair coated with gel and placed (taped) on the bottom of the UAV. This area of interest is still developing and needs further research, as well as the biological control and release of beneficial insects.

Other Areas of UAV Utilization

Besides remote sensing operations and interventional applications, precision agriculture opens new areas for possible UAV utilization. High potential of UAV utilization can be seen in animal production, which is a crucial part of the agriculture sector providing both food and animal products.

Livestock production is essential in animal production contributing to food security, nutrition, poverty alleviation, and economic growth. Approximately 30% of the Earth's terrestrial areas are occupied with livestock systems. For high-quality food production and to meet the needs for food safety, animal welfare according to the World Organisation for Animal Health (WOAH) is crucial. Pasture-raised and open-raised environments not only include welfare benefits but also allows UAVs to be utilized in such environments (Soumya et al., 2022; Arulmozhi et al., 2024; WOAH, 2025). UAVs might be used in livestock production for various purposes using UAV imagery and video surveillance. Some of the main areas of utilization according to (Alanezi et al., 2022) are included in Table 3.

As Table 3 shows, there are numbers of possible uses of UAVs in livestock production. For data collection and practical uses, high potential can be seen in operations such as livestock counting, detection, animal position and monitoring of health status and behaviour. Such operations provide valuable data for the implementation with smart technologies and help farmers to easily notice any changes.

Table 3. UAV utilization in livestock production

Area of Utilization	Purpose
Detection and counting	Detecting, locating and counting livestock
Tracking while grazing	Tracking the livestock while grazing
	Tracking the misplaced livestock
Communication and exploratory agency	Shepherding the livestock
	Collecting data of livestock position
Health monitoring	Monitoring livestock temperature and blood pressure (UAV in combination with RFID tags attached to the ears of animals)
Behaviour monitoring	Monitoring feeding behaviour
	Capturing feeding patterns
Livestock roundup	Gathering livestock together
Estimation of livestock distribution	Understanding the spatial and temporal distribution of the livestock in the pastures

The rapid development of UAVs might also influence other operations and processes in animal production. As aquaculture is part of agriculture, UAVs have a potential in the feeding of fish in fishponds. Chavande & Bagde (2024) describe, that in aquaculture, automated UAV systems are revolutionizing the feeding process by distributing feed pellets over ponds at regular intervals. UAVs involved in the feeding process are equipped with a rotary disc placed under the tank, similar to fertilizer spreading and seeding UAVs. The feed (in form of solid granules) is then dispersed from the UAV.

Besides animal production, there are other possible areas for UAV utilization. Table 4 shows more possible areas for UAV implementation and includes recent studies.

Table 4. Other areas for UAV utilization

Area of Utilization	Recent Studies	Description
Environmental studies	Burgués & Marco (2020)	Environmental chemical sensing providing dense 3D air quality measurements
	Almalki et al. (2021)	Real time monitoring of environmental parameters in combination with IoT and ground sensors
Heat loss detection	Tanda et al. (2020)	UAV-based thermal-imaging approach for monitoring of waste disposal sites with focus on detecting heat loss and biogas leakages
Wildlife	Beaver et al. (2020)	Wildlife estimation and monitoring using UAVs with thermal sensors

UAV REGULATIONS AND ADOPTION CHALLENGES

It is evident that the utilization of UAVs in precision agriculture significantly contributes to the agricultural sector. However, it also faces complex challenges and limitations that require particular attention. These challenges can be identified in the following sections.

Regulatory Limitations

Different regulations of UAV operations are applied worldwide. In Europe, the European Union Aviation Safety Agency (EASA) is heading towards the development of harmonized regulations for UAV utilization. Within the member countries of the European Union, the regulatory framework consists of two legal acts - Regulation (EU) 2019/947 (focusing on operational requirements and procedures, e.g. operator registration, remote operator´s certificate) and Regulation (EU) 2019/945 (focusing on technical certification requirements, e.g. design, manufacturing, maintenance and third-country operations). The regulations are also applicable to certain non-EU countries that are part of EFTA (European Free Trade Association), and which participate in the EASA system as part of their ties with the European Union, e.g. including countries Switzerland, Liechtenstein, Norway, and Iceland (EASA, 2024).

In other regions worldwide, civil aviation administrations and authorities are responsible for UAV regulatory. For instance, in China (Civil Aviation Administration of China), in Australia (Civil Aviation Safety Authority) or in the United States of America (Federal Aviation Administrations). However, regulations worldwide may vary, leading to some countries with very strict UAV regulatory frameworks or almost forbidden use of UAVs (Nazarov et al., 2023; Global Drone Regulatory Database, 2025).

The major challenge that persists for broader UAV adoption is the Beyond Visual Line of Sight (BVLOS) operation. Such operations include e.g. large-scale monitoring and sensing of agricultural land. BVLOS operations can be executed under specific conditions and require special permits and operator registrations. Furthermore, when integrating UAV autonomy to BVLOS operations, additional regulatory challenges may appear. BVLOS regulations are currently varying worldwide, thus international harmonization of regulations is highly recommended to enhance the adoption of UAVs in agriculture and unlock their full potential (Matalonga et al., 2022; Nazarov et al., 2023).

One of the strictest regulations regarding UAV utilization is in spraying applications. The potential of Unmanned Aerial Spraying Systems (UASS) is evident; however, it needs further improvement in available data. The strictest regulations apply for UASS pesticide spraying. Many parameters of UASS may affect the overall spraying quality, including the number and position of the rotors; number, type, location and configuration of the spraying nozzles; distance between the nozzles and the vertical distance between the rotors and the nozzles under them. Furthermore, there are several more operational parameters needed to be considered, including flight path planning; spraying height; application rate (volume adjustment); swath width; appropriate nozzle type; droplet penetration rate, deposition and drift (Ozkan, 2024; García-Munguía et al., 2024).

Besides the operational parameters of UASS, the application of pesticides must consider several additional factors, for instance human toxicology; operator and bystander exposure; dietary exposures; environmental fate and behaviour;

ecotoxicology; physical and chemical properties; and efficacy. The most important and vulnerable data for safe UASS applications are related to exposure, efficacy, and spraying drift. Some of the published data on UASS performance may not be relevant and can be contradictory because of the wide variation of design parameters among UASS being tested. Additional research and published data are needed to make conclusive statements on overall safety of UASS applications (OECD, 2021).

Technological Limitations

Although UAV technology has many benefits, it still faces technological limitations that need to be overcome, to maximize its potential. These limitations include lack of technological and communication infrastructure (for isolated and rural areas) leading to troubles with connectivity; UAV battery life and power maintenance; operational parameters - the maximum payload, level of autonomy; sensor reliability and accuracy; overall equipment reliability etc. (García-Munguía et al., 2024; Guebsi et al., 2024; Khan et al., 2024) for instance:

Remote sensing operations – Sensor precision, reliability and acquired data accuracy are crucial, particularly in various climatic conditions, highlighting the need to develop more robust sensors.

Interventional applications – Limited autonomy and restricted maximum payload capacities are currently present, including power, structural and flight safety limitations. The development of light-weight structures with higher payload capacities and improved autonomy is crucial. Additionally, for spraying applications, there is an increasing need for improvements in UAV flexible spray control software, and the incorporation of flow meters to track and record the actual amount of spray applied.

Adoption Barriers

Different adoption barriers regarding UAV utilization may be identified. There are obstacles for slower adoption among farmers, including the high initial costs of UAV technology and software; necessary training and skills development; and lack of knowledge and UAV promotion in this sector. Especially for small farmers it is difficult to allocate resources for the higher initial investment of UAV technology due to the limited access to capital. For rural areas and developing countries, barriers may also include the lack of technological infrastructure; insufficient technical skills of farmers; and the resistance to change. Broader adoption needs better awareness strategies and proper training to enhance the skills of farmers (Kushwaha et al., 2023; Puppala et al., 2023).

Ethical Considerations and Data Privacy

With the easy access to UAV technology and its broader adoption in various sectors, concerns may arise including ethics, privacy and safety. Critical questions may be identified about privacy protection, informed consent, and potential impacts on the interference of built-in and natural environments. In agriculture, these ethical considerations are particularly relevant concerning data collection practices. It is crucial for farmers to follow ethical guidelines and to ensure, that the use of UAV technology respects privacy rights and does not violate the rights of neighbouring landowners or local communities. In terms of data collection, questions about data privacy may arise. It is essential to protect data privacy in today's era of information overload. Secure data storage and transmission is needed to prevent data breaches and data missuses. Moreover, other impacts of UAVs should be considered, including potential environmental impacts, such as disturbances to wildlife or local ecosystems caused by frequent aerial flights (Guebsi et al., 2024; Hoek Spaans et al., 2024).

FUTURE TRENDS AND PROMISING RESEARCH AREAS IN UAV TECHNOLOGY

The UAV technology is rapidly developing in recent years, which leads to a broader utilization of this technology in digital agriculture. As for remote sensing, the future trend is heading towards high-accuracy detailed sensing of both crops and soils, with the emphasis on precise data. Such data would supplement the informational databases of satellite sensed data and significantly contribute to better results, enhancing the decision-making processes. For interventional applications, the future development is heading towards more reliable and safer systems with high level of autonomy and increased maximum payload capacities. Besides these trends, new promising research areas can be identified, following:

Harvesting – The development of harvesting UAVs might be a big frontier in UAV automation. A harvesting UAV equipped with advanced computer vision and robotic arms would be able to identify, precisely pick (harvest), temporarily store and transport the harvested crops. The potential is seen in harvesting fruits and vegetables. Harvesting UAVs would contribute to increased efficiency especially in large orchards or vegetable fields and help to replace the already missing human labour. However, challenges remain in terms of identifying the optimal harvesting time, maximum payload capacity and the ability to handle such crops without causing damage to them (Guebsi et al., 2024; Moshayedi, et al., 2024).

Transporting – The popularity of transporting UAVs is rising in the industrial and delivering sector. However, for agricultural products transportation, challenges remain in terms of maximum payload capacity and the big volumes that are being moved on a daily basis. However, this technology would be suitable for the transport of smaller objects such as spare parts, phytosanitary products and certain goods (Savaniu et al., 2022). Due to the ongoing development of UAVs with bigger and bigger payload capacities, the novelty will be seen in different areas too, such as the transportation of feed, water barrels or animals to remote or inaccessible terrains.

UAVs in Indoor and Controlled Environments – Precision field tasks similar to outdoor UAV operations may be carried out indoors too. This leads to the integration of UAVs in greenhouse environments, as they are well suited for autonomous UAV tasks. For other indoor environments, such as vertical farms, innovation is leading towards the development of micro-UAVs. These micro-UAVs could revolutionize crop management in controlled environments by enabling continuous, non-invasive monitoring and rapid response to changes and problems. However, factors such as the lack of GPS information in an indoor environment, the presence of obstacles and a limited flight area make the UAV control difficult in indoor environments, thus further research and development is needed (Aslan et al., 2022; Guebsi et al., 2024).

As mentioned above, the potential of UAVs can be seen in various new research areas. The recent development leads to the integration of UAVs and Artificial Intelligence (AI). That is already transforming the sector of digital agriculture by optimizing processes and available resources to the new technological revolution Agriculture 5.0. The combination of AI, robotics and UAV techniques is a promising approach towards farm operations optimalization and farm automation processes. Potential of UAV and AI integration can be already seen in crop management, prediction and classification; disease and pest management; soil management; water management and fertigation; weed detection and agricultural supply chain and logistics management (Abreu & van Deventer, 2022; Oliveira & Silva, 2023; Son et al., 2024). As for more complex agricultural systems and technologies, research areas can be identified for the following areas:

UAV Autonomy – The synergy between UAV and AI has led to a notable progress in the autonomy of UAVs, that are capable of completing complex missions without direct human supervision. UAV autonomy can be significantly improved by AI, optimizing processes such as autonomous behaviour and real-time decision-making. Few aspects regarding to UAV autonomy can be identified, as the optimization of UAV trajectories; detection and recognition of objects in real time; and the development of autonomous navigation systems. The synergy of AI and UAV autonomy is a promising research area for future development (Caballero-Martin et al., 2024).

Team Deployment of UAVs (Swarming) – The future direction of UAVs is heading towards the development of AI-driven UAVs and team deployment of UAVs, also referred to as UAV swarming or UAV swarms. The development of UAV swarms could allow more efficient and coordinated monitoring of large agricultural areas and synchronized data acquisition. One of the potential areas of UAV swarm utilization is the development of accurate, real-time, reliable, and autonomous UAV-based systems for crop diseases identification and weed detection. UAV swarms may be utilized in UAV interventional applications, e.g. spraying, fertilizer spreading, seeding. Furthermore, the ongoing development of harvesting UAVs may be a suitable area for UAV swarm utilization in order to increase the harvesting efficiency. However, challenges remain in terms of the optimal UAV path planning, communication, obstacle avoidance and possibilities of malfunctions, thus additional research is needed (Bouguettaya et al., 2022; Ming et al., 2023; Guebsi et al., 2024).

UAV Integration in Unmanned Farms – An unmanned farm is a production model, which does not require human labour for carrying out various operations and tasks. Unmanned farms include a variety of systems for fully automated and intelligent management, such as sensors, Big Data, IoT, 5G, UAV, AI, robots etc. An automated unmanned farm represents the highest level of agricultural production. Various systems are used for monitoring the environment, growth status of agricultural animals and plants, the working status of various operating equipment, efficient data transmission and storage to the clouds. An unmanned farm is capable of precise planning, optimizing every process and self-decision making (Wang, T. et al., 2021; Ming et al., 2023). In particular, UAVs may contribute to the system of an unmanned farm by efficient data collection and precise AI analysis of acquired data. Moreover, the utilization of UAVs in specific field operations (e.g. targeted spraying) and team deployment tasks is a promising tool for the enhancement of unmanned farms. In this context, UAVs significantly contribute to the whole production system of unmanned farms (Ming et al., 2023; Padhiary et al., 2024; Moshayedi et al., 2024).

AI Analysis of Data – Precision agriculture includes enormous amount of farming data related to meteorological information, soil and crop conditions, marketing demands, and land uses. The integration of AI has a big potential in analysing UAV collected data in combination with machine learning and deep learning algorithms (Zhai et al., 2020). Potential can be seen in analysing UAV-based aerial images, e.g. in crop pests and disease identification, weed identification, plant counting or yield prediction. Recent studies combining UAV data and AI analysis are shown in Table 5. The integration of AI to data-processing and analysis also opens new perspectives for predictive analysis in agriculture. Furthermore, implementing 5G technology alongside with AI promises enhanced data transfer rates and real-time analytics, which will revolutionize the agricultural decision-making processes, that are currently mainly human based. Thus, agricultural decision support systems based on artificial intelligence decision models and UAV data are a promising research area for future development.

Table 5. Recent studies combining UAV data and AI analysis

Area of Utilization	Recent Studies	Description
Crop disease identification	Bouguettaya et al. (2022)	A survey on deep learning-based identification of crop diseases from UAV-based aerial images. The survey highlighted various UAV sensors (RGB, multispectral, hyperspectral, thermal) adopted to identify crop diseases. Different deep learning models were used to identify crop and plant diseases from aerial images were presented
Crop yield prediction	Fei et al. (2022)	A study focused on machine-learning algorithm analysing UAV-based multi-sensor data in order to predict yields in wheat
Weed detection	Catala-Roman et al. (2024)	An AI-based autonomous UAV swarm system for weed detection and spraying treatment

In summary, it is evident that AI plays a crucial role in the future direction of UAV technology development, opening new promising research areas for UAV autonomy, AI-driven UAVs and data analysis. For enhanced crop production, the greatest potential can be seen in UAV team deployment and integration to both manned and unmanned farm. Due to the agricultural operations realized in open field conditions, the quick transfer and intervention of machinery without damage to the soil and crop is important. This is opening the potential for UAVs in various areas, as their key advance over ground machinery is that no soil compaction is present. Soon, unmanned farms and systems are expected to become popular. For future UAV farm systems, it is expected that almost no tracks will be present in field caused by ground machinery, thus bringing the potential for larger arable area and higher yields. In this context, this will be crucial for future agricultural crop production, considering the increasing number of world population.

CONCLUSIONS

This literature review highlighted the importance of UAV technology in the transformation process of the agricultural sector. The aim of this review was to point out the future trends and importance of linking the technology of UAV with AI as one of the basic tools of the latest technological revolution Agriculture 5.0. The literature review focused on the utilization of UAV technology in precision agriculture, with the emphasis on the novelties, future trends and promising research areas.

UAVs have become integral to various applications in agriculture, where they enhance the efficiency and sustainability of the agricultural systems in the face of recent worldwide challenges such as climate change and food security. The effective utilization of UAVs in precision agriculture hinges on understanding both spatial and temporal variability in soil and crop characteristics. UAVs enhance the data acquisition and efficient monitoring by advanced sensing technologies.

In remote sensing operations, the novelties can be seen in precise data acquisition of both crops and soils characteristics, including the utilization of high-resolution RGB, multispectral and LiDAR sensors. Precise UAV collected data are expected to supplement the already existing datasets of satellite data. The importance of AI in the UAV data acquisition and post-processing is expected to rise, due to the emergence of AI data analysis tools and machine and deep learning algorithms.

The increasing integration of UAVs in precision agriculture also significantly affected the interventional applications of various inputs. The highest potential can be seen in precise, targeted applications of inputs, especially for spraying applications. However, the major challenges in this area are the regulatory and technological limitations in terms of safety and spraying quality. Due to the wide variation of design parameters among spraying UAVs, additional research is needed to make conclusive statements on overall safety of spraying UAVs. Regulatory disparities between countries worldwide are limiting the potential of UAVs in both remote sensing operations and interventional applications, thus harmonization efforts need to be implemented.

For other areas of UAV utilization, practical implementation can be identified in animal production too, especially in livestock production. UAVs play a crucial role in operations such as livestock counting, detection, animal position and monitoring of health status and behaviour, providing valuable data and enhancing the quality of animal production systems. For future directions of possible UAV utilizations, potential can be seen in the field of harvesting, transportation and implementation to indoor controlled farm environments.

Looking ahead, the future of UAVs is very promising. The linkage between UAV and AI is significantly enhancing various agricultural operations. Future trends can be identified in the promising research areas, such as the development of AI-driven UAVs, UAV swarms and enhanced UAV autonomy. Moreover, high potential can be seen in the integration of UAVs to unmanned farms. Further integration of AI alongside with IoT and 5G will provide fast and efficient data transfer and revolutionize the agricultural decision-making processes in real-time. Soon, the rise of fully automated farming systems that require minimal human intervention is expected.

In conclusion, UAVs are an integral part of the agricultural sector and are being positioned as irreplaceable tools for addressing the current agricultural challenges of the 21st century. Realizing the benefits of UAV and AI technology and the potential for future implementation areas, a close cooperation between farmers, industry and policymakers will be needed to overcome various regulatory, technical and socio-economic challenges. For a clear and healthy agricultural sector, it is crucial to find a balance between the technological possibilities of UAVs with AI, and the respect to data-privacy and socio-ethical considerations. Moving forward, both farmers and ordinary people will be influenced by the upcoming rapid advent of technology and must be ready to adapt to the incoming changes.

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