

REVIEW

Open Access



Advancements of drone utilization in crop production: a systematic review

Stewart Ategeka^{1*} and Attila Bai¹

Abstract

Amidst the exponential global population growth, the integration of drones into precision crop production emerges as a pivotal strategy for optimizing agricultural processes. With projections indicating a required increase of over 60% in food production to feed the 9.7 billion people by 2050, optimizing agricultural practices becomes imperative. In this study, the utilization of drones in precision crop production was investigated through a systematic review of literature published in the Web of Science database between 2000 and 2022. Through a systematic review, the research aimed to assess the publication trends, research focus areas, and key operations related to drone use in precision crop production. Literature analysis using *VOSviewer 1.6.18* software revealed a significant increase in publication activity, particularly from 2016 onwards, reflecting growing interest and advancements in drone technology in precision crop production. The United States emerged as the global leader in research on drone applications in precision crop production, followed by China and Australia. Notably, the Mann–Kendall and Sen's Slope trend analysis indicated a significantly increasing tendency in the domain's publication activity ($p < 0.0001$, $S = 0.25$). Key research areas included remote sensing, deep learning, and vegetation indices, with wheat, maize, and cotton being the most studied crops. The most significant drone operations included deep learning, vegetation indices, phenotyping, and yield estimation, individually with a total link strength of 25, 10, 7, 7, and 7, respectively. The study recommends expanding research on drone applications across diverse crops, including horticultural crops, and strengthening support for the participation of low and lower-middle-income countries to enhance the accessibility and relevance of drone technology in agriculture.

Keywords Aerial systems, Precision crop production, Drones, Remote sensing, UAVs

Introduction

The best test of this century is how to confront the rising demand for food needed by the continuously growing world population. The world population is projected to have an increment of 2 billion people in the following 30 years, and to about 9.4 to 10 billion people by 2050 [1]. A huge increase in food production must be realized to meet the needs of the rapidly growing world population. The initial projections indicated that to feed the world

population by 2050, world food production needed to increase by 70% [2], later projections were revised, indicating a required increase in food production of 60% in order to feed the world population [3]. Population expansion, climate change, and natural resource over-exploitation trends have triggered innovative and better methodologies to produce food [4]. The structure of agriculture has progressively changed from many small farms to fewer larger farms, facilitating economies of scale that enhance production efficiency and lower costs. This has been due to labor-displacing mechanisms, new policies favoring industrial-scale production, specialization, and pressure to increase output while reducing costs [5], favoring the adoption of Precision crop production due to its ability to optimize input usage.

*Correspondence:

Stewart Ategeka
ategeka.stewart@gmail.com

¹ Faculty of Economics and Business, University of Debrecen, 138 Bösörményi út, 4032 Debrecen, Hungary



© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

Precision crop production is advocated for due to its ability to optimize inputs for better returns on investment, a decrease in agriculture's negative environmental impacts, and a more conducive farming workspace. The primary objective is to guarantee that the appropriate treatments are applied in the proper location and at the correct period [6]. Precision crop production technologies such as drones, Global Positioning System (GPS), and real-time kinematics (RTK) optimize crop production. Optimization is achieved due to the ability of these technologies to provide timely critical information on weather, soil conditions, and plant health status [7]. Precision crop production is an innovative approach to agricultural management that utilizes digital tools to monitor and enhance farm production processes [8].

Precision crop production involves the utilization of the variability between and within the fields and climate to upgrade input allocation and improve productivity through optimization. Precision crop production promotes effectiveness by spatially focusing the application of inputs to where they generally have the highest productivity, accordingly, maximizing results for a given blend of resources [9]. Besides, drones are used in monitoring, and application of pesticides, herbicides, and fertilizers in crops, timely and efficiently [10].

Given the recent advancements in drone technology, new aviation regulations governing the use of such systems have emerged. The use of drones in agriculture demands safe integration into the aviation setting through strict regulations that could enable large-scale applications, with the possibility for farmers to safely fly beyond the visual line of sight [11].

Research shows that some countries have progressed in the use of drones because of favorable policies while others have stagnated [12]. Some scholars argue that precision technologies have a low impact on the farm's net returns, but the benefits are both actual and perceived and significantly vary by the type of technology applied [9].

Whereas Unmanned Aerial Vehicles (UAVs)/drones have a wide range of applications in precision crop production, selecting the most suitable task for their application is influenced by social and economic factors such as the cost of the technology, attitude, and farmers' level of education [13]. Evidently, the application of drones in precision crop production encounters several challenges, such as requiring flight control expertise, the effect of weather conditions such as wind and light, coverage limitations due to energy budgets, limited flight time, the need for ground equipment for controls and decisions, and restrictions due to policies and regulations [14]. It is therefore vital to map and analyze such published studies through a literature review to create a knowledge base,

highlight the limits to knowledge, and define potential gaps for future research (Tranfield et al. 2003). This study seeks to provide an evidence-based assessment of the most effective applications of drones/UAVs in precision crop production by: (i). Assessing the research and development trends of the published studies on drone usage in precision crop production between the years 2000 and 2022. (ii). Analyzing the key evidence-based operations for the application of drones in precision crop production, and (iii). To identify nationally important crops for drone applications

Literature review

Brief history of drones in agriculture

One spearheading step in the use of drones in crop production was recorded in 1906, when John Chaytor applied a hot air balloon guided by ropes from the ground to spread grass seed in New Zealand. The licensed innovation by Nikola Tesla in 1898 allowed ropes to later be replaced by a radio wave-based system [15]. In agricultural aerial imagery, an early application involved a lightweight radio-controlled aircraft equipped with a gimbal-mounted 35 mm camera to capture high-resolution vertical images illustrating competition levels between oilseed rape and weeds [16]. In 1987, Yamaha introduced the R-50, which it set out as the first pilotless helicopter for crop spraying that could practically be used. Nevertheless, this innovation was still at the test stage. A commercial version of the R-50 was presented on the market in 1989. This technology was not user-friendly due to its weight. Users were not permitted to purchase one of their own, all things considered, Yamaha decided to lease them to clients, and the offer included training [15]. In 1991, the Swedish University of Agricultural Sciences (SLU) began a venture to develop an aircraft with a camera to map crop trials [17]. Later, a Hungarian engineer Laslo Kiss constructed a methanol-driven RC-aircraft that was roughly 3 m wide and weighed 17 kg, whereas Anders Larsolle and colleagues made the primary tests in 1992 with infrared photography applied to late blight in potato [15]. Initially developed for military and security objectives, drones achieved a major breakthrough in crop production around 2011, marking their emergence as valuable tools in agriculture [18]. Because of the accelerated developments in innovation and technology, drone capabilities have constantly evolved since the mid-nineteenth century. This was because the technology became relatively inexpensive and less complicated to use due to the use of automated electronic flight controls like gyro, and electrical engines as opposed to fueled engines. Similarly, the development of electrical batteries with high power and less weight, enabled more admissible flight time (in excess of 5 minutes) [15]. The

increased accessibility of technologies such as global navigation satellite system (GNSS), Inertial Measurement Units (IMU), lithium polymer (LiPo) batteries and electric speed controllers (ESC) for brushless motors in combination with new micro-processors, and imaging systems greatly contributed to the increased usage of drones in civil operations, including precision crop production [19]. The gradual advancements in the use of drones for precision crop production activities have since attracted increased research, leading to a substantial publication activity of related literature.

Precision crop farming

Precision crop farming is an idea based on observing or sensing and altering management operations/activities depending on the spatial and temporal variability in crops and crop needs, which can be simplified to site-specific crop management. The concept of precision crop farming is guided by “sensing” as a primary component [10]. Sensors in fields and crops are utilized to generate miniature data of interest on soil conditions in addition to extensive data on climate, plant nutrition requirements, water availability, and pest and disease invasions. Broadly, mixed, and separate technologies are applied to achieve distinct objectives in precision crop production such as soil property evaluation [20], precision seeding [21], precision irrigation [22], precision fertilization [21], precision spraying [23], remote sensing and monitoring [24], and creating possibilities for inter-communications and linking technology to farm machinery [25, 26]. Exceptionally, the use of drones in precision crop production is multifunctional, with the ability to independently execute precision operations or complement the process.

Understanding the term “drone”

A drone or an unmanned aerial vehicle (UAV) is defined by the International Civil Aviation Organization as an aircraft flown without a pilot on board [27]. Another related term, Unmanned Aircraft System (UAS) is referred to as the unit comprised of parts like a drone, the controllers (based on ground), and the communication framework between the two (the drone and the operator) [28]. Remotely Piloted Aircraft System (RPAS), referred to as a remotely guided aircraft, is related to remote pilot station(s), the necessary command and control links, plus some other components in accordance with the design type specification. Remotely Piloted Aircraft (RPA), is an automated aircraft operated remotely from a pilot station [27]. All the above terms allude to a drone that is operated by a pilot on the ground or pre-modified to fly specific routes [29]. According to the UK Aviation Authority, drones are categorized into civil and military, where military drones are designed for defense operations with

advanced capabilities, while civil drones are used for commercial and recreational purposes with simpler technology [30].

UAV/Drone application in precision crop production

In a bid to enhance efficiency, crop production has realized some technological advancements that help farmers in upgrading optimization through the accurate use of inputs. Drone technology, one such innovation, has acquired popularity in farming [31]. Research shows that various optical sensors are linked to global positioning systems (GPS), and geographic information systems (GIS) to record the position of the readings that can accurately be mapped to facilitate monitoring and variable rate application of inputs in a wide range of crops such as maize, cereals, brassica and ryegrass [32]. Depending on the type of analysis or data to be collected and crop, various cameras such as multispectral, red, green, and blue (RGB), thermal cameras, hyperspectral and other consumer-grade low-cost cameras are modified, fixed on drones to capture near-infrared (NIR) pictures [33]. The use of drones along with other Information Communication Technologies (ICTs) are developing a unique stage in the agribusiness space where we have digitized farming, e-agriculture, smart agriculture, and precision crop production [34]. Drones, equipped with powerful data collection tools, are the most complex systems that have ever graced farmers' fields. With the help of sensors attached to drones, data collection from a square-mile field could be achieved in a few hours, transferred, accumulated into huge data, decoded, and interpreted for practical use. Nowadays, researchers' ability to convert raw data into useful intuitions has upgraded, increasing farmers' potential to reap more benefits from the increased efficiency of the new UAV technological systems [35].

Publication activity on the application of drones in precision crop production

The remarkable increase in research publications regarding drone application in agriculture calls for condensing the broad literature and discovering the realm's rationale within various studies. Since drone technology is consistently improving, systematic reviews must be carried out regularly to digest current literature and establish critical gaps for research [36]. Various scholars have examined the general use of drones in agriculture, presented various drone classifications, system and technological pros and cons, applications, and future potentials. For example, Rahman et al. [37] argued that quadcopter drones have been conferred as the widely used type of drones in agriculture due to their excellent aeronautics and ability to convey larger payloads. In addition, the greatest

advantages were their ability to improve efficiency, save costs on inputs and minimize environmental pollution.

On the contrary, the high cost of the technology, the need for extensive software and hardware knowledge, the effect of severe weather conditions, and personal privacy were some of the major limitations to drone use in crop monitoring and spraying operations. Furthermore, Puri et al. [38] reviewed the role of drones in agriculture and emphasized the technical characteristics. Discretely, other scholars reviewed the application drones for specific precision crop farming operations, for example, weed detection [38], plant breeding [39], crop biomass monitoring [40], and spraying [41, 42].

The increasing availability of literature has enabled review studies on drone application in specific categories of crops, for example, in orchards [43]. Additionally, it has also been possible to conduct review studies on the use of drones in single crops such as sugarcane [44]. Currently, it is practically possible to summarize and synthesize literature through structured reviews focusing on a narrow and specific subject area on the use of drones and the level of precision in crop production.

Due to safety and ethical concerns, national and supra-national regulatory bodies publish guidelines, regulations, and policies to govern the use of drones. For example, the International Civil Aviation Organization (ICAO) drafts and publishes guiding policy frameworks on drones for National Aviation Organizations [27]. The European Aviation Safety Agency (EASA) drafts similar policies for EU member states [45]. Unfortunately, in many developing countries, such guiding policies have not been drafted and published or have been drafted but unpublished, limiting accessibility and hindering related studies. For example, a study by Jeanneret and Rambaldi [46] shows that only 7 of the 48 African, Caribbean and Pacific (ACP) countries¹ in Africa had drone rules and policies in place, pending approval in 4 countries, while 37 countries had no policies and regulations in place. On the other hand, developing countries are progressively drafting and publishing legal documents governing the use of drones. For example, Uganda now has a detailed drone policy that includes the prohibition of operations in the interest of safety and security and restrictions on dropping or discharging any objects unless authorized [47]. These, among other provisions, could potentially limit the use of drones in precision crop operations such as spraying, which involves aerial object discharge.

Essentially, the literature published includes primary scholarly articles investigating the use of drones for

specified operations in precision crop production, secondary studies such as review articles and books, grey literature, and legal documents like statutes and circulars. To gain novel insights into drone use in precision crop production, researchers ought to maximize the use of multiple data sources and literature types.

Trends in the annual growth of published literature

Various trends can be traced in the publication activity within the domain of drones and agriculture, as well as precision crop production, since the evolution of drone technology. A review by Rejeb et al. [36] that utilized the Scopus database and focused on drones and their general application in agriculture between 1990 to 2021, in an attempt to show the temporal distribution of English, peer-reviewed journal articles, two different stages could be identified that is the build-up stage (1990–2010), with an annual average publication of only 7 papers, and the growth-stage (2010–2021) which showed a significant increase in the number of publications per year with 1275 journal articles published in the year 2020. A similar review by Delavarpour et al. [48] aimed at defining the features of drones used in crop spraying and field monitoring, and the practical challenges associated. Without limitation to the start period, the authors found that over 50% (~3000) of the publications in the Web of Science database had been published in the period after the year 2016. It can be asserted that the publication activity on the use of drones in precision crop production steadily expanded after the year 2010 and exponentially increased after the year 2016. Although the body of literature is consistently expanding, certain aspects of drone use in precision crop production remain substantially under-represented. For example, feasibility studies aiming to assess the economic efficiency of drone use in precision crop production can hardly be retrieved from any database [48]

Materials and methods

Research design

The research design was based on content analysis, which involves the study of recorded human communications, such as scientific literature, laws, and constitutions [49]. The technique helps to systematically categorize, code, and quantify data to reveal both the visible and hidden meaning behind the content [50]. To generate scientific proof, a systematic review was conducted to identify, evaluate, and deduce evidence relevant to each research question. A realistic review criterion was applied to further synthesize the literatures. A realistic review can be applied as a means of determining what worked for whom, in what circumstances, in what respect, and how. The Systematic Literature Review (SLR) protocol was

¹ Botswana, Côte d'Ivoire, Kenya, Madagascar, Nigeria, Rwanda, South Africa.

followed. The key steps in the protocol included determining research questions, identifying literature databases, establishing search keywords, searching databases, finding primary studies, conducting quality checks, extracting data, and synthesizing [51].

Identification of databases and literature

Presently, there are various databases used to generate scientific literature, such as Scopus, Web of Science, Google Scholar, and PubMed, and each of these employs a unique approach in its research disciplines. Whereas Scopus is one of the most preferred databases due to the high number of records and its application of the peer review technique for research validation [52], Web of Science was selected for this study after conducting scoping searches as prescribed by [53], and it was found to contain more articles relating to the research topic compared to other databases. The Web of Science (WOS) database is also appreciated for containing the most respectable and prominent journals and is, in this way, appreciated as the most definitive information hotspot for concentrating studies and accessing publications on most subjects [54].

Literature search procedure

The search keywords used were: UAV, Unmanned Aerial Vehicle, Drones, Remotely Piloted Aircraft System, RPAS, Unmanned Aircraft System, UAS, crop production, and crop farming. The search string was: (UAV or "Unmanned Aerial Vehicle" or Drones or "Remotely Piloted Aircraft System" or RPAS or "Unmanned Aircraft System" or UAS) AND ("crop production" or "crop farming"). The search was limited to topic (title, abstract and keywords).

Inclusion and exclusion criteria

To ensure quality, all articles were carefully screened according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards as defined by [55, 56]. Articles were included if they were published in English, contained the keywords for each search equation for the respective objectives, and met the specified criteria. This aligned with Snilstveit [57], who highlighted the importance of critical validation of all studies before inclusion in any review as a means of quality assessment. A total of 153 documents were published between 2000 and 2022. The period from 2000 to 2022 was selected to capture significant advancements in agricultural research and technology, particularly in remote sensing and precision agriculture, which have seen rapid growth since the early 2000s [43]. Additionally, this time-frame aligns with the increasing use of digital tools in agriculture, as highlighted by recent studies showing a surge in related publications after 2000 [36, 58]. Through

a screening process, 7 documents were eliminated after limiting the document type to articles, and 40 articles were further excluded after limiting the search by topic and English language. The final number of articles used for the bibliometric analysis was 76. The 76 articles were manually screened through full reading to identify specific articles to address objective two. The screening was guided by the following question: Was there a specific crop production operation or experiment? Answers: (a) yes (growth monitoring and vegetation mapping, spraying, pest and disease detection, spraying, seeding, fertilization, yield estimation, soil mapping, other remote sensing operations), (b) no (something different), (c) unclear. Only articles with a yes answer were considered (63) to address objective 2.

Data analysis

To assess research and development trends in drone use for precision crop production from 2000 to 2022, a bibliometric analysis was conducted. Bibliometric analysis involves the application of mathematics and measurable methods to books and different media of communication. It is a scientific study detailing the measurement of the process by which information is transferred. Bibliometric analysis can be summarized as the logical investigation of recorded discourse [59]. *VOSviewer 1.6.18* software was used to analyze different research publications. *VOSviewer* software provides the most significant features for investigating and detailing recent research trends in different subject areas. For example, [60] applied *VOSviewer* to analyze advances in precision coffee growing research. Units for analysis in this study included years of publication, authorship, country, institutions, document citation, link strengths, and Keywords. In bibliometric analysis, link strength quantifies the intensity of the relationship between two items, such as authors, institutions, keywords, or publications and a research subject, while in bibliographic coupling, a link represents the connection between two articles, and its numerical value indicates the strength of that connection, with higher values reflecting stronger relationships [61].

Authorship as a unit of analysis helps identify key contributors and collaborations within a research field, allowing for the mapping of influential researchers and their impact on the evolution of specific topics. Furthermore, results were coded and analyzed using Excel to test the significance of various variables. The Mann–Kendall trend test/Two-tailed test was run to determine the statistical significance of the publication trend at a 5% significance level and 95% confidence interval (Sen's slope). Results were summarized and presented in tables and graphs.

To determine the key evidence-based operations for the application of drones in precision crop production, articles were scanned through full reading to identify the types of crops and the related operations for the application of drones. Results were further classified according to the geographical location of the experimental site by country.

Results and discussions

Status of research on drone use in precision crop production

The annual publication activity on the use of drones in precision crop production presents three stages. Stage 1: between 2000 to 2008 with no publication, stage 2: from 2009 to 2015 with 5 publications, and stage 3: from 2016 to 2022 with 71 publications (Fig. 1).

Stage 1: was attributed to the earlier decades when drones were primarily designed for military operations [18]. After 2008, there was a growing interest in consumer drones, resulting in their first introduction to some European, Asian, and North American markets. Several drone manufacturing companies, such as DJI, Parrot, and 3DRobotix, have advanced research and development to design and produce consumer drones for various civil operations, including agricultural applications. The substantial increase in the number of publications between 2016 and 2022 is largely attributed to the significant decrease in prices for consumer drones, which made them more affordable to farmers. It is not surprising that the consumer electronics report by Statista [62] presents exactly similar trends and phases in the consumer drone market, as shown in Fig. 2. The results also conform to the study by Rejeb et al. [36] who attributed the post-2010 growth in publications on the use of

drones in precision agriculture to the development of complementary technologies such as hyperspectral sensors and artificial neural networks (ANN).

The Mann–Kendall trend test/Two-tailed test (Table 1) indicates a significant positive trend in the growth of the publication activity on the utilization of drones in precision crop production.

Based on two hypotheses, that is the null hypothesis (H_0): There is no trend in the series, the alternative hypothesis (H_a): There is a trend in the series, the computed p-value was lower than the significance level $\alpha=0.05$, resulting in the rejection of the null hypothesis H_0 , in favor of the alternative hypothesis H_a , indicating a significant growing trend in the subject's publication, with the observed pattern more closely conforming to an exponential growth trend as indicated by the Sen's slope (Fig. 3). Similarly, Simonton [63] contended that breakthrough ideas occur infrequently and by chance, thus asserting that the frequency of attempts increases the likelihood of success, which highlights the significance of increased research activity to technological advancements, including drone technologies in precision crop production.

Level of research participation

The results indicate that, currently USA is the global leader in research related to the use of drones in precision crop production with 28 publications, followed by China (22), and Australia (7) (Fig. 4).

The USA's market of agricultural drones was valued at USD 1,197.05 million in 2021 and is expected to increase to about USD 6,029.86 million by 2030, at a Compound Annual Growth (CAGR) rate of 19.68% from 2023 to 2030 [64]. It is no wonder that the USA is leading in

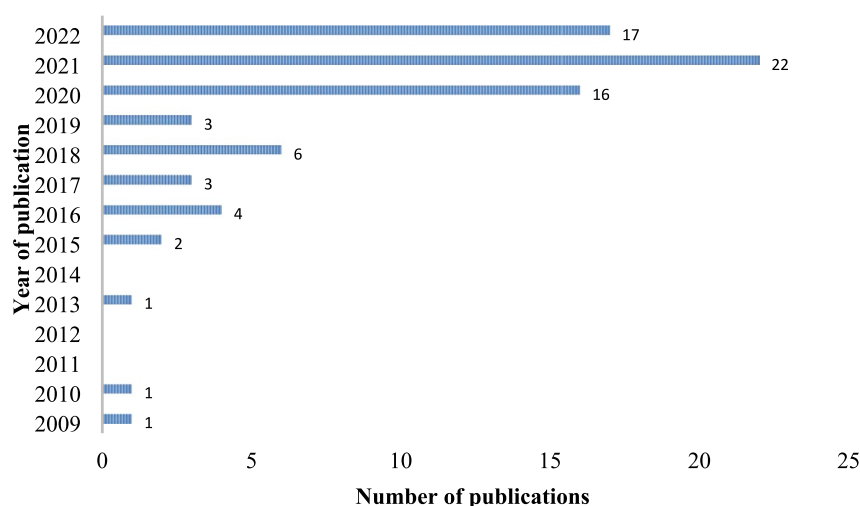


Fig. 1 Annual Article publication on precision crop production. Source Own editing based on search string 1 results from the Web of Science

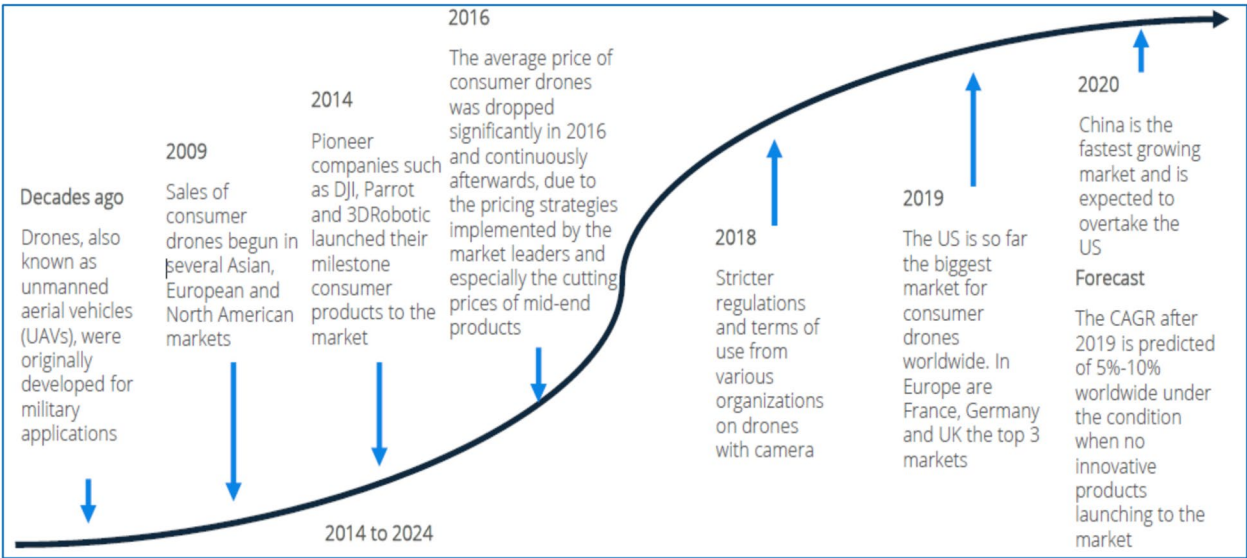


Fig. 2 Worldwide consumer drone market stages. *Source* Adopted from Statista [62]

Table 1 Mann–Kendall trend test/two-tailed test

Series\Test	Kendall's tau	p-value	Sen's slope
Number of articles published	0.748	< 0.0001	0.250

Source Author's own calculations based on search string 1 results

the number of publications regarding the use of drones in precision crop production. In addition, the USA has also significantly invested in drone research, for example, through the National Institute for Food and Agriculture, Kansas City State University was awarded more than \$100,000 for a drone research program aimed at

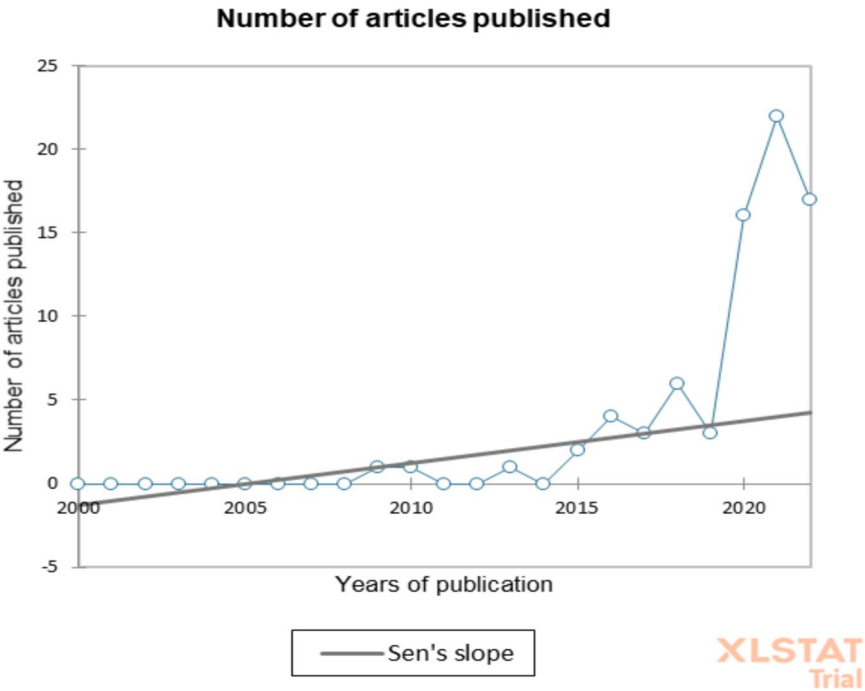


Fig. 3 Sen's slope on the article publication trend. *Source* Author's own analysis based on search results from the Web of Science

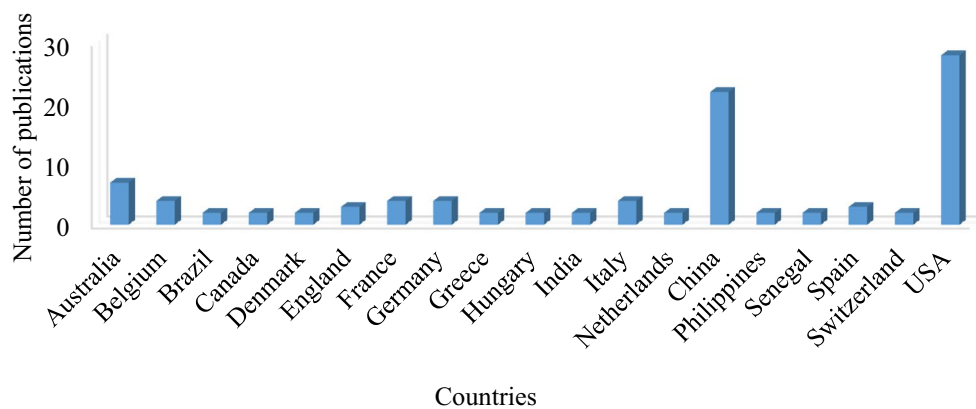


Fig. 4 Global leading (countries) on the use of drones in precision crop production researchers. *Source* Own analysis based on search results from the Web of Science

improving the use of drones in the USA's major crops, such as wheat and other grains (Mordor [65]).

Moreover, a report by Drone Industry Insights [66] showed that the highest number of drone manufacturing companies are based in the USA and China. Three out of the top 5 civil drone manufacturing companies are based in China, with DJI company on top of the list, while 3 out of 5 of the top 5 dual-use drone manufacturing companies are based in the USA, with Aero-Vironment at the top of the list. Another important aspect that greatly influences research publications is the availability and access to research grants. The National Natural Science Foundation of China currently stands out as the world's leading research funding agency. Out of the 76 publications analyzed, 13 (17%) were funded by the National Natural Science Foundation of China, followed by the United States Department of Agriculture with 4 publications (5%). [67] found similar results, with China leading the publication on the application of drones in precision crop production and the National Natural Science Foundation of China having funded the majority (18%) of the publications.

Geographically, North American, Asian, European, and South American countries dominated in the number of publications. There was limited research from African countries, with only Senegal among the top 10 leading global researchers, having 2 publications.

Level of research and collaboration between institutions and organizations

The overlay visualization of co-authorship by organization indicates that the Chinese Academy of Science is the world's leading institution in research and collaboration on the use of drones in precision crop production, followed by Wuhan University (China), and Aarhus University (Denmark) (Fig. 5). The size of the circle indicates an

organization's level of publication and collaboration with other organizations. The highest level of collaboration was between Chinese organizations, and this is partly so because of the similarity in the language. Lately, there has been a growing level of collaboration with organizations outside China, for example, between the two Chinese universities (Hunan Normal University and Chinese Academy of Science) with Leibniz Institute of Agricultural Development in Transition Economies (Germany) and the University of Antwerp (Belgium) indicated by the red circles. Contrary to Peter et al. [68], who found a positive correlation between the number of publications and citation levels, the Chinese organizations had the most collaborations, implying more publications, yet the most influential documents were from the Agricultural Research Service of the USA (4 documents with a total of 189 citations).

It can be asserted that increased collaboration between research institutions from different countries could potentially improve the impact of scholarly publications. The level of collaboration is crucial as it enhances knowledge sharing, fosters innovation, builds capacity, and strengthens the credibility and overall effectiveness of research projects, as evidenced by studies highlighting the benefits of collaborative networks in research [69–71]. The higher collaboration from Chinese institutions can be attributed to strong funding incentives from the National Natural Science Foundation of China (NSFC) that prioritize interdisciplinary research and partnerships with international scholars at top-tier Chinese institutions and private sector involvement [41, 42], geographic proximity that reduces costs and eases coordination [72, 73], and the role of language, as the growing English proficiency of Chinese researchers facilitates international scientific communication and lowers collaboration barriers [74].

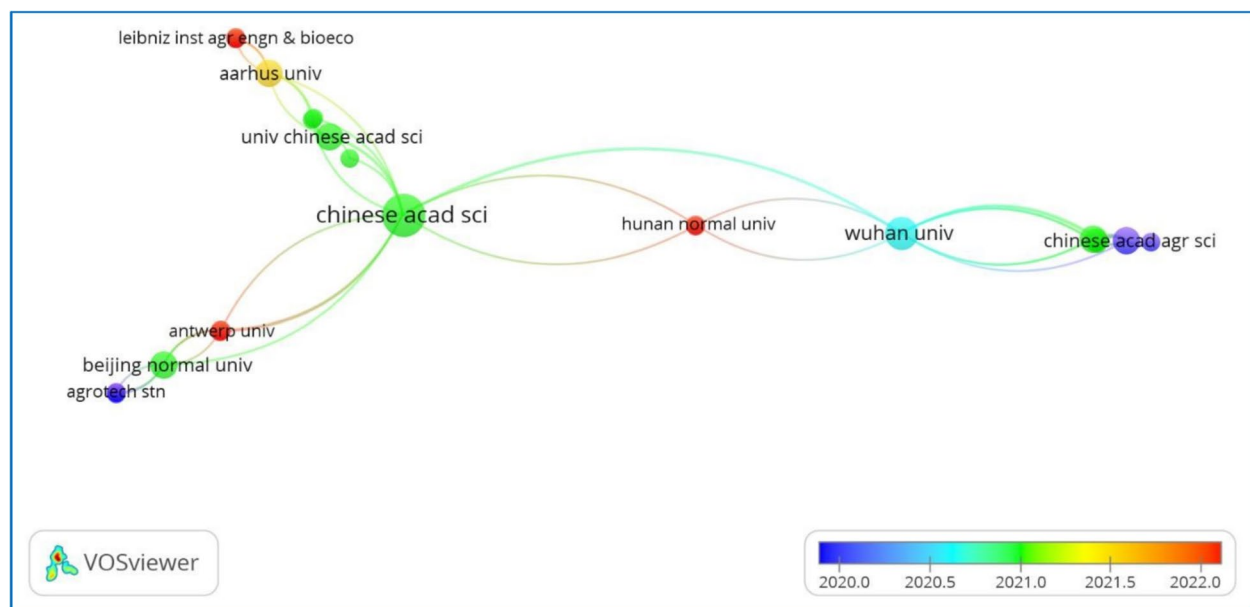


Fig. 5 Research participation and collaboration of organizations. Source Own result with VOSviewer software based on search string 1 results

Moreover, national programs such as the International Cooperative Program for Innovative Talents explicitly encourage global collaboration as part of China's strategy to enhance scientific visibility and leadership [75], as reflected in partnerships with institutions such as Aarhus University in Denmark and the University of Antwerp in Belgium.

Key research areas in the use of drones in precision crop production

Analysis of the co-occurrence of author keywords shows that the current focus areas of research are remote sensing, deep learning, vegetation indices, phenotyping, and yield estimation, each with a total link strength of 25, 7, 7, 7, respectively (Fig. 6). Other vital areas of research were photogrammetry, multispectral sensors, biomass, and various indices used in understanding vegetation density and analyzing critical changes in plant health such as leaf area index, Normalized Difference Vegetation Index (NDVI), and other models useful for growth monitoring and pest inspection, such as Faster-R-CNN (Region-based Convolutional Neural Network).

Interestingly, object detection can be identified as one of the latest areas of focus within various publications (red circle). This highlights the significance of drones in growth monitoring and vegetation mapping-related operations. It is worth noting that UAV (Unmanned Aerial Vehicles) is the most common term used to refer to drones in most publications.

Crops most researched with drones in leading countries

From the articles analyzed, a total of 24 crops were studied by different authors through experiments. This included wheat, maize, cotton, rice, rapeseed, barley, grapes, soybean, potatoes, apples, sugarcane, banana, bambara groundnuts, olives, alfalfa, peanuts, sorghum, millet, peas, camelina, oats, almond, chicken peas, and walnuts. The rest of the publications were about non-crop-specific farm operations, and others focused on environmental tests. Wheat was the most studied crop with a total of 13 studies, and it was most studied in China in 6 different study sites. The second most studied crops were maize and cotton, with a total of 9 publications each. Cotton was most studied in the USA, in 5 different experimental sites, whereas maize was most studied in China in 4 different study sites. However, the distribution of crops studied reveals notable gaps. While staple and industrial crops such as wheat, maize, and cotton dominate the literature, research on vegetable crops like cabbage, onions, and lettuce remains limited. This imbalance is compounded by the relatively low engagement of low and lower-middle-income countries, which may hinder the generation of context-specific knowledge and the adoption of drone technologies in settings where such crops are crucial for food security and smallholder livelihoods. Figure 7 presents the top 10 most-studied crops in the utilization of agricultural drones among the world's top 10 leading countries.

Wheat, maize, and rice are the world's most important cereal crops [58]. China is the world's biggest producer

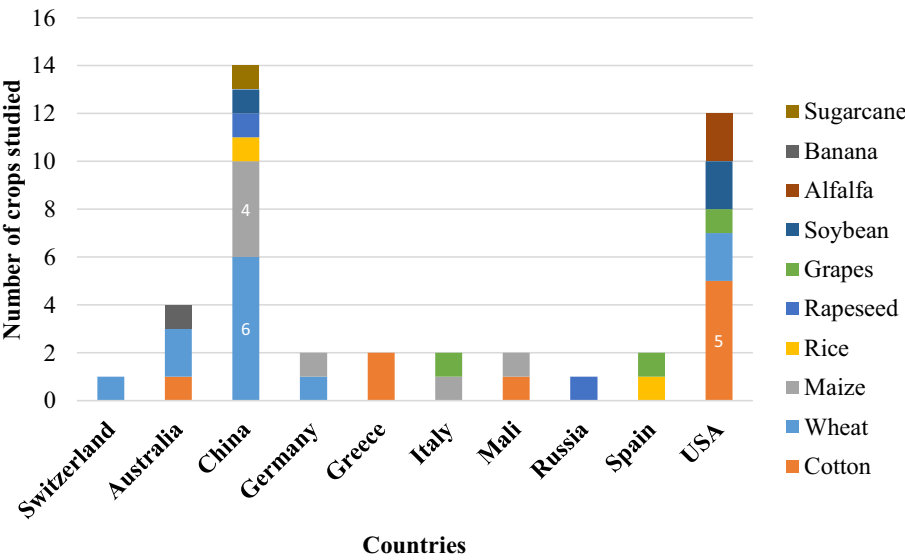
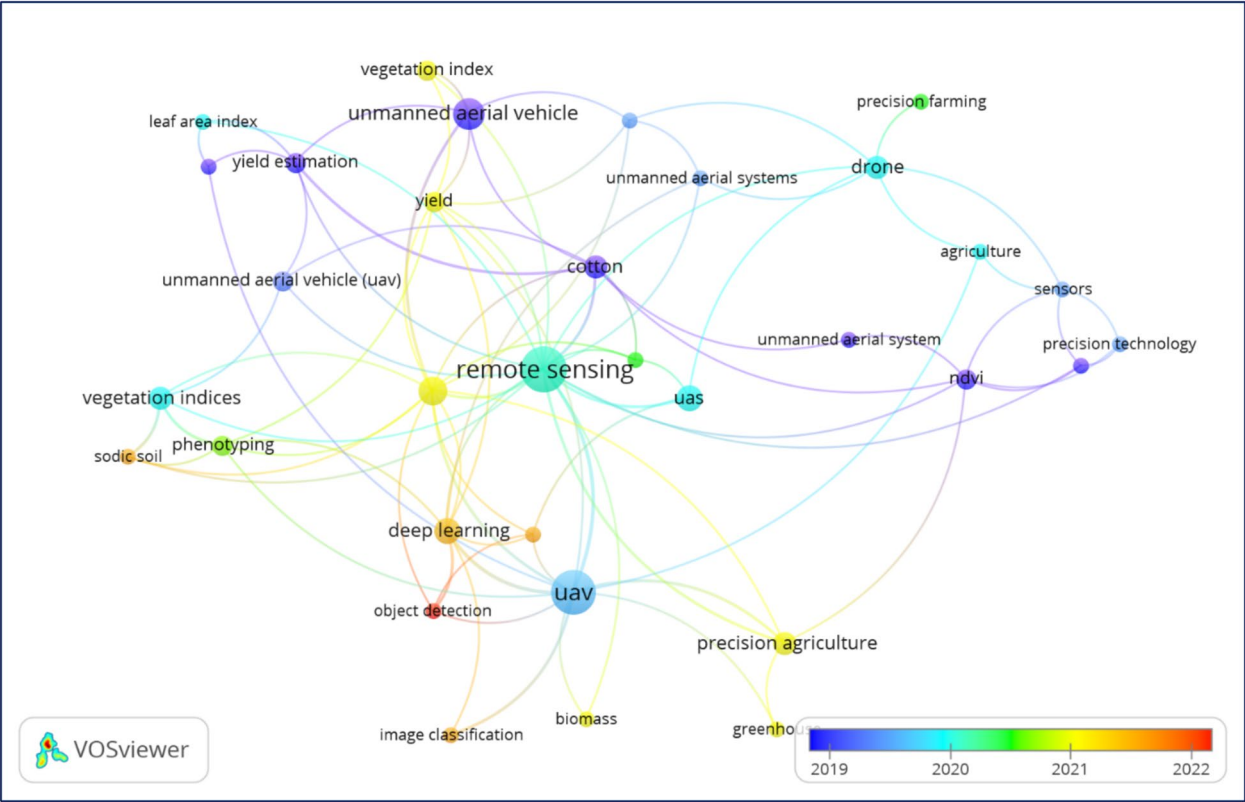


Fig. 7 Most studied crops and the location of the experimental sites. Source Own analysis based on full article reading results from 76 articles

and consumer of wheat [76]. Wheat is uniquely treasured in China and used to make special foods like noodles, buns, dumplings, and many pastries. According to FAO

[76], the USA and China are the world’s leading countries in the production of maize, with annual production of 384 and 272.6 million tons, respectively. Maize plays

a significant role in both countries, mainly for livestock feed, fuel ethanol production and processing of several food and industrial products such as corn oil, starch, sweeteners, and industrial alcohols. On the other hand, China is the global leader in the production of cotton (seed, unginned), with a total production of 17.4 million tons, while the USA is the third after India with a total production of 11.2 million tons. It can be deduced that the economic role of these crops (wheat, maize, and cotton) in the USA and China defined the countries' research efforts to optimize resource use, enhance production and profitability through drones. The production of maize and wheat in the USA and China has steadily increased over the years. In 1961, China produced 18,027,091 tonnes of maize, while the USA produced 91,388,000 tonnes. By 2023, these figures had risen to 289,086,202 tonnes for China and 389,694,460 tonnes for the USA. Similarly, wheat production increased from 14,294,248 tonnes in China and 33,539,008 tonnes in the USA in 1961 to 136,596,100 tonnes in China and 49,313,930 tonnes in the USA in 2023, as shown in Fig. 8. This significant increase in maize and wheat production highlights the growing need for innovative technologies, such as drone research, to monitor and optimize agricultural practices for enhanced productivity.

Key drone applications in precision crop production

Results show that the most common operations for the utilization of drones in precision crop production include growth monitoring, vegetation mapping, yield estimation, pest inspection, spraying, soil mapping, and other remote sensing operations, such as monitoring a farm's irrigation system. From the top 10 most studied crops

(Table 2). Growth monitoring and vegetation mapping were mainly in wheat, cotton, and maize. Yield estimation was mainly in cotton and soybean, while spraying was mainly in rapeseed. Interestingly, the drone applications were dominated by remote sensing operations mainly focused on the collection of data on the field conditions and crop growth status.

The data focus areas included germination status, pest and disease detection, nutrient deficiencies, drought stress, the impact of various treatments, and other field conditions such as lodging. Consequently, spatial field data were utilized to create management zones. Consistent with Tsouros et al. [78], this study elucidates that remote sensing operations, including weed mapping, growth monitoring, and vegetation mapping, currently represent the predominant applications of drone technology within the realm of precision crop production. Remote sensing operations utilize low-weight sensors that are easily conveyed by drones. Nonetheless, heavier loads such as pesticides and fertilizers can also be conveyed although such operations are limited by payload capacity and lower flight time [14].

Conclusion

Results showed a significant level of research interest in the use of drones in remote sensing, deep learning, cotton, vegetation indices, phenotyping, and yield estimation, each with a total link strength of 25, 12, 10, 7, 7, and 7, respectively. The USA was the global leader in research related to the use of drones in precision crop production, with 28 publications, followed by China (22). The Mann–Kendall and Sen's Slope trend analysis indicated a significantly increasing tendency in the domain's

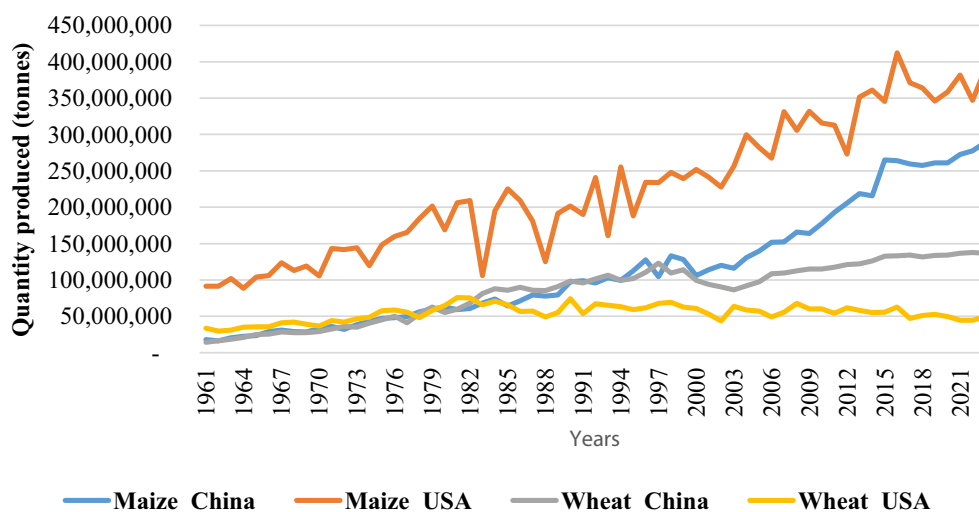


Fig. 8 Annual maize and wheat production for China and the USA from 1961 to 2023. Source Own result with data from [77]

Table 2 Operations for drone applications in the top 10 studied crops

Crop	Number of articles per drone applications for the top 10 studied crops					
	Spraying	Growth monitoring and vegetation mapping	Pest scouting	Yield estimation	Soil mapping	Other remote sensing operations
Wheat		10		2		
Cotton		6		3	1	
Maize		6	1	2	1	
Rice		1	1	1		
Rapeseed	3	2		1		
Grapes		2				1
Soybean		1		3		
Alfalfa				1	1	1
Banana		2				
Sugarcane	1	1				
Total	4	31	2	13	3	2

Source Author's own calculations based on search string 1 results

publication activity ($p < 0.0001$, $S = 0.25$). Most research focused on drone use in intensive industrial cultivars like wheat, cotton, maize, and bananas. Despite the growing body of research on drone applications in precision crop production, significant gaps remain. In particular, the application of drones in non-industrial crops, such as cabbage, onions, and lettuce is underrepresented in the literature. Moreover, this research domain is further constrained by the limited engagement and collaboration of low and lower-middle-income countries, including African countries, which may restrict the development of context-specific innovations and slow the diffusion of drone technologies in regions where such crops are vital for food security and livelihoods.

The study recommends expanding research on drone applications across diverse crops, including horticultural crops, and strengthening support for the participation of low and lower-middle-income countries to enhance the accessibility and relevance of drone technology in agriculture. A key limitation of this review was its exclusive reliance on the Web of Science (WoS) database. Although WoS offers broad coverage and rigorous indexing that enhances study quality and reliability, this reliance may have limited the review's scope by omitting relevant research not indexed in the database. Additionally, the focus on peer-reviewed journal articles was intended to ensure methodological rigor as they underwent stringent review processes. However, this may have excluded valuable insights from other sources, such as conference proceedings and reports. Given these limitations, future research could incorporate multiple databases and varied publication types to enhance the review's scope and depth.

Acknowledgements

Ocwa, Akasairi (Institute of Land Use, Engineering and Precision Farming Technology, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi street, 4032, Debrecen, Hungary) provided technical support on the software that was used for data analysis (VosViewer) and in the study design.

Author contributions

SA conceptualized the study, searched for data, analyzed, and interpreted the results, and was a major contributor in writing the manuscript. AB provided all the mentorship, technical guidance, review, and corrections of the entire manuscript. All authors read and approved the final manuscript.

Funding

There was no special funding for this study.

Availability of data and materials

All data supporting the findings of this study are available within the paper and any Supplementary Information can be shared on request. The search string for the review was: <https://www.webofscience.com/wos/woscc/summary/c2c0d00d-74c2-459a-be0a-bfa29d3af12d-725e1ba3/relevance/1>

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 8 April 2024 Accepted: 29 September 2025

Published online: 08 May 2026

References

1. U.N. World population prospects 2019 data booklet; 2019.

2. F.A.O. How to feed the world in 2050; 2009. https://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf
3. Alexandratos N, Bruinsma J. World Agriculture towards 2030/2050: the 2012 revision; 2012. www.fao.org/economic/esa
4. Menchaca A. Sustainable food production: the contribution of genome editing in livestock. Sustainability. 2021. <https://doi.org/10.3390/su13126788>.
5. Brown DL, Schafft KA. Rural people and communities in the 21st century; 2019.
6. Cherkasov GN, Nechaev LA, Koroteev VI. Precision agricultural system in modern terms and definitions. Russ Agric Sci. 2009;35(5):334–8. <https://doi.org/10.3103/S1068367409050139>.
7. Nyaga JM, Onyango CM, Wetterlind J, Söderström M. Precision agriculture research in sub-Saharan Africa countries: a systematic map. Precis Agric. 2021;22(4):1217–36. <https://doi.org/10.1007/s11119-020-09780-w>.
8. Petrović B, Bumbálek R, Zoubek T, Kuneš R, Smutný L, Bartoš P. Application of precision agriculture technologies in Central Europe-review. J Agric Food Res. 2024;15:101048.
9. DeLay ND, Thompson NM, Mintert JR. Precision agriculture technology adoption and technical efficiency. J Agric Econ. 2022;73(1):195–219. <https://doi.org/10.1111/1477-9552.12440>.
10. Monteiro A, Santos S, Gonçalves P. Precision agriculture for crop and livestock farming—brief review. Animals. 2021. <https://doi.org/10.3390/ani11082345>.
11. Popescu D, Stoican F, Stamatescu G, Ichim L, Dragana C. Advanced UAV-WSN system for intelligent monitoring in precision agriculture. Sensors. 2020. <https://doi.org/10.3390/s20030817>.
12. Stöcker C, Bennett R, Nex F, Gerke M, Zevenbergen J. Review of the current state of UAV regulations. Remote Sens. 2017. <https://doi.org/10.3390/rs9050459>.
13. Bai A, Kovách I, Czibere I, Megyesi B, Balogh P. Examining the adoption of drones and categorisation of precision elements among Hungarian precision farmers using a trans-theoretical model. Drones. 2022. <https://doi.org/10.3390/drones6080200>.
14. Mukherjee A, Misra S, Raghuwansi NS. A survey of unmanned aerial sensing solutions in precision agriculture. J Netw Comput Appl. 2019;148:102461.
15. Frankelius P, Norrman C, Johansen K. Agricultural innovation and the role of institutions: lessons from the game of drones. J Agric Environ Ethics. 2019;32(5–6):681–707. <https://doi.org/10.1007/s10806-017-9703-6>.
16. Thurling DJ, Harvey RN, Buller NJ. Aerial photography of field experiments using 50 remotely-piloted aircraft. British Crop Protection Conf. (1985);357–63.
17. Andersson A. Pests and diseases. In: 34th Swedish Crop protection conference; 1993.
18. Peña K. Accountability for private security contractor drone operators on the U.S.-Mexico border: applying lessons learned from the Middle East. Public Cont Law J. 2014;44(1):137–56.
19. Rokhmana CA. The potential of UAV-based remote sensing for supporting precision agriculture in Indonesia. Procedia Environ Sci. 2015;24:245–53.
20. Boursianis AD, Papadopoulou MS, Diamantoulakis P, Liopa-Tsakalidi A, Barouchas P, Salahas, Karagiannidis G, Wan S, Goudos SK. Internet of Things (IoT) and agricultural unmanned aerial vehicles (UAVs) in smart farming: a comprehensive review. Internet of Things. 2022;18:100187. <https://doi.org/10.1016/j.iot.2020.100187>
21. Kazlauskas M, Sarauskis E, Romaneckas K, Steponavicius D, Jasinskas A, Naujokiene V, et al. Effect of variable rate seeding on winter wheat seedbed and germination parameters using soil apparent 16 electrical conductivity. Eng Rural Dev. 2021;20:1108–13. <https://doi.org/10.22616/ERDev.2021.20.F240>.
22. Adeyemi O, Grove I, Peets S, Norton T. Advanced monitoring and management systems for improving sustainability in precision irrigation. Sustainability. 2017;9(3):353. <https://doi.org/10.3390/su9030353>.
23. Tona E, Calcante A, Oberti R. The profitability of precision spraying on specialty crops: a 53 technical-economic analysis of protection equipment at increasing technological levels. Precis Agric. 2018;19(4):606–29. <https://doi.org/10.1007/s11119-017-9543-4>.
24. Mazzetto F, Gallo R, Importuni P, Petrer S, Sacco P. Automatic filling of field activities register, from challenge into reality. Chem Eng Trans. 2017;58:667–72. <https://doi.org/10.3303/CET1758112>.
25. Kay W, Zahra L, Ed A. The drone industry barometer 2022. Consolidating new trends and perspectives of the commercial drone industry; 2022. <https://droneii.com/wpcontent/uploads/2022/08/drone-industry-barometer-2022.pdf>
26. Pearson. Scarfone A, Picchio R, del Giudice A, Latterini F, Mattei P, Santangelo E, Assirelli A. Semi-automatic guidance vs. manual guidance in agriculture: a comparison of work performance in wheat sowing. Electronics (Switzerland). 2021;10(7). <https://doi.org/10.3390/electronics10070825>
27. ICAO. Manual on remotely piloted aircraft systems (RPAS) (Doc 10019); 2015. <https://store.icao.int/en/manual-on-remotely-piloted-aircraft-systems-rpas-doc-10019>
28. ICAO. Cir 328, Unmanned aircraft systems (UAS); 2011. https://www.icao.int/meetings/uas/documents/circular%20328_en.pdf
29. Nelson J, Gorichanaz T. Trust as an ethical value in emerging technology governance: the case of drone regulation. Technol Soc. 2019;59:101131.
30. Cunliffe AM, Anderson K, DeBell L, Duffy JP. A UK Civil Aviation Authority (CAA)-approved operations manual for safe deployment of lightweight drones in research. Int J Remote Sens. 2017;38(8–10):2737–44. <https://doi.org/10.1080/01431161.2017.1286059>
31. Kim HG, Park JS, Lee DH. Potential of unmanned aerial sampling for monitoring insect populations in rice fields. Fla Entomol. 2018;101(2):330–4. <https://doi.org/10.1653/024.101.0229>.
32. Hedley C. The role of precision agriculture for improved nutrient management on farms. J Sci Food Agric. 2015;95(1):12–9.
33. Haghghattalab A, González Pérez L, Mondal S, Singh D, Schinostock D, Rutkoski J, Ortiz Monasterio I, Singh RP, Goodin D, Poland J. Application of unmanned aerial 38 systems for high throughput phenotyping of large wheat breeding nurseries. Plant Methods. 2016;12(1):35. <https://doi.org/10.1186/s13007-016-0134-6>
34. El Bilali H, Allahyari MS, China Agricultural University. Transition towards sustainability in agriculture and food systems: role of information and communication technologies. Inf Process Agric. 2018;5(Issue 4):456–64. <https://doi.org/10.1016/j.inpa.2018.06.006>.
35. Basso B, Dobrowolski J, McKay C. From the dust bowl to drones to big data: the next 31 revolution in agriculture. Georget J Int Aff. 2017;18:158–65. <https://doi.org/10.1353/gja.2017.0048>.
36. Rejeb A, Abdollahi A, Rejeb K, Treiblmaier H. Drones in agriculture: a review and bibliometric analysis. Comput Electron Agric. 2022;198:107017.
37. Rahman MFF, Fan S, Zhang Y, Chen L. A comparative study on application of unmanned aerial vehicle systems in agriculture. Agriculture (Basel). 2021. <https://doi.org/10.3390/agriculture11010022>.
38. Puri V, Nayyar A, Raja L. Agriculture drones: a modern breakthrough in precision agriculture. J Stat Manag Syst. 2017;20:507–18. <https://doi.org/10.1080/09720510.2017.1395171>.
39. Jang GJ, Kim J, Yu JK, Kim HJ, Kim Y, Kim DW, et al. Cost-effective unmanned aerial vehicle (UAV) platform for field plant breeding application. Remote Sens. 2020. <https://doi.org/10.3390/rs12060998>.
40. Mohidem NA, Che'ya NN, Juraimi AS, Ilahi WFF, Roslim MHM, Sulaiman N, Saberion M, Noor NM. How can unmanned aerial vehicles be used for detecting 49 weeds in agricultural fields? Agric (Switzerland). 2021;11(10). <https://doi.org/10.3390/agriculture11101004>
41. Chen H, Lan Y, Fritz B, Hoffmann C, Liu S. Review of agricultural spraying technologies for plant protection using unmanned aerial vehicle (UAV). Int J Agric Biol Eng. 2021;14:38–49. <https://doi.org/10.25165/j.ijabe.20211401.5714>
42. Chen X, Zhang Z, Guo J. Output regularities of China's international collaboration research projects funded by NSFC. Library Hi Tech. 2021;39(4):951–69. <https://doi.org/10.1108/LHT-03-2020-0075>.
43. Zhang C, Valente J, Kooistra L, Guo L, Wang W. Orchard management with small unmanned aerial vehicles: a survey of sensing and analysis approaches. Precis Agric. 2021. <https://doi.org/10.1007/s11119-021-09813-y>.
44. Barbosa Júnior MR, Moreira BRA, de Brito Filho AL, Tedesco D, Shiratsuchi LS, da Silva RP. UAVs to monitor and manage sugarcane: integrative review. Agronomy. 2022;12(3). <https://doi.org/10.3390/agronomy12030661>

45. EASA. Easy access rules for unmanned aircraft systems (regulations (EU) 2019/947 and 2019/945); 2020.
46. Jeanneret C, Rambaldi G. Drone governance a scan of policies, laws and regulations governing the use of unmanned aerial vehicles (UAVs) in 79 ACP countries. CTA Working Paper;16/12; 2016. <https://cgspace.cgiar.org/server/api/core/bitstreams/5182448f-8f52-4128-991de830341b5c47/content>
47. UCAA. The civil aviation (unmanned aircraft systems) regulations; 2022.
48. Delavarpour N, Koparan C, Nowatzki J, Bajwa S, Sun X. A technical study on UAV characteristics for precision agriculture applications and associated practical challenges. *Remote Sens*. 2021. <https://doi.org/10.3390/rs13061204>.
49. Earl B. The practice of social research (15th ed.). Cengage; 2021.
50. Saunders MNK, Lewis P, Thornhill A. Research methods for business students (18th ed.); 2019.
51. Kitchenham B, Brereton P, Budgen D, Turner M, Bailey J, Linkman S. Systematic literature reviews in software engineering—a systematic literature review. *Inf Softw Technol*. 2009;51:7–15. <https://doi.org/10.1016/j.infsof.2008.09.009>.
52. Lengyel P, Bai A, Gabnai Z, Mustafa OMA, Balogh P, Péter E, et al. Development of the concept of circular supply chain management—a systematic review. *Processes*. 2021. <https://doi.org/10.3390/pr9101740>.
53. Boland A, Cherry G, Dickson R. Doing a systematic review: a student's guide. SAGE Publications; 2017. <https://books.google.co.uk/books?id=H1AIDwAAQBAJ>
54. Zhao X, Zuo J, Guangdong W, Huang C. A bibliometric review of green building research 2000–2016. *Archit Sci Rev*. 2018;62:1–15. <https://doi.org/10.1080/00038628.2018.1485548>.
55. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ*. 2009;339:b2535. <https://doi.org/10.1136/bmj.b2535>.
56. Purssell E, McCrae N. How to perform a systematic literature review: a guide for healthcare researchers. *Practitioners Students*. 2020. <https://doi.org/10.1007/978-3-030-49672-2>.
57. Snijlsteit B. Systematic reviews: from 'bare bones' reviews to policy relevance. *J Dev Eff*. 2012;4(3):388–408. <https://doi.org/10.1080/19439342.2012.709875>.
58. Rejeb A, Abdollahi A, Rejeb K, Treiblmaier H. Drones in agriculture: a review and 55 bibliometric analysis. *Comput Electron Agric*. 2022b;198:107017. <https://doi.org/10.1016/j.compag.2022.107017>
59. Ronald R, Leo E, Raf G. Becoming metric-wise. A bibliometric guide for researchers. Elsevier Ltd.; 2018. <https://doi.org/10.1016/C2017-0-01828-1>
60. Santana LS, Ferraz GAES, Teodoro AJdaS, Santana MS, Rossi G, Palchetti E. Advances in precision coffee growing research: a bibliometric review. *Agronomy*. 2021. <https://doi.org/10.3390/agronomy11081557>.
61. Ullah F, Shen L, Shah SHH. Value co-creation in business-to-business context: a bibliometric analysis using HistCite and VOS viewer. *Front Psychol*. 2023. <https://doi.org/10.3389/fpsyg.2022.1027775>.
62. Statista. Consumer electronics: market data & analysis; 2012b. <https://www.statista.com/study/55488/consume-electronics-market-report/?locale=en>
63. Simonton DK. Creativity in science: chance. *Logic Genius Zeitgeist*. 2004. <https://doi.org/10.1017/CBO9781139165358>.
64. V.M.I. Global agricultural drones market size by component (batteries, camera systems, controller systems, navigation systems), by application (livestock monitoring, precision farming, precision fish farming), by geographic scope and forecast; 2022.
65. Mordor Intelligence. Agriculture drones market—growth, trends, and forecast (2023–2028); 2023. <https://www.mordorintelligence.com/industry-reports/agriculture-drones-market/market-size>
66. Drone Industry Insights. Drone manufacturers ranking 2022; 2022. <https://droneii.com/product/dronemanufacturers-ranking>
67. Singh AP, Yerudkar A, Mariani V, Iannelli L, Glielmo L. A bibliometric review of the use of unmanned aerial vehicles in precision agriculture and precision viticulture for sensing applications. *Remote Sens*. 2022. <https://doi.org/10.3390/rs14071604>.
68. Peter VDB, Sandström U, Nil AB. Does quantity make a difference? The importance of publishing many papers; 2015. <https://arxiv.org/ftp/arxiv/papers/1510/1510.01871.pdf>
69. Green BN, Johnson CD. Interprofessional collaboration in research, education, and clinical practice: working together for a better future. *J Chiropr Educ*. 2015;29(1):1–10. <https://doi.org/10.7899/jce-14-36>.
70. Nalmpanti AD, Wong CY, Oghazi P. Collaborating for innovation: the inhibiting role of constraints. *J Innov Knowl*. 2024. <https://doi.org/10.1016/j.jik.2024.100504>.
71. Susan Van G. The effectiveness of knowledge sharing and collaboration in the effectiveness of knowledge sharing and collaboration in creating high performance work teams creating high performance work teams; 2011. <https://digitalcommons.pepperdine.edu/etd/170>
72. Ma H, Fang C, Pang B, Li G. The effect of geographical proximity on scientific cooperation among Chinese cities from 1990 to 2010. *PLoS ONE*. 2014. <https://doi.org/10.1371/journal.pone.0111705>.
73. Scherngell T, Hu Y. Collaborative knowledge production in China: regional evidence from a gravity model approach. *Reg Stud*. 2011;45(6):755–72. <https://doi.org/10.1080/00343401003713373>.
74. Wei R, Kong M, Wang J. The role of English at key Chinese universities: English-medium instruction, international cooperation, and English-language websites. *Int J English Acad Purposes Res Pract*. 2023;3(2):171–84. <https://doi.org/10.3828/ijeap.2023.10>.
75. Wang C, Jesiek B, Zhang W. Elevating international collaboration and academic outcomes through strategic research funding: a bibliometric analysis of China Scholarship Council funded publications. *Scientometrics*. 2024;129(7):4329–51. <https://doi.org/10.1007/s11192-024-05054-8>.
76. FAO. Production quantity for crops and livestock products; 2021. <https://www.fao.org/faostat/en/#data>
77. FAOSTAT. Production quantity for crops and livestock products; 2025. <https://www.fao.org/faostat/en/#data>
78. Tsouros DC, Bibi S, Sarigiannidis PG. A review on UAV-based applications for precision agriculture. *Information*. 2019. <https://doi.org/10.3390/info10110349>.
79. Petrović B, Bumbálek R, Zoubek T, Kuneš R, Smutný L, Bartoš P. Application of precision agriculture technologies in Central Europe—review. *J Agric Food Res*. 2024;15:101048. <https://doi.org/10.1016/j.jafr.2024.101048>
80. Moysiadis V, Sarigiannidis P, Vitsas V, Khelifi A. Smart farming in Europe. *Comput Sci Rev*. 2021;39:100345.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.