Gomal Journal of Agriculture and Biology
Vol: 3 -- Issue: 2, 2025
Https://gomalpublishers.com/GJAB
Support@gomalpublisher.com
ISSN: 3007-1364 (Print)
ISSN: 3007-1372 (Online)

PRECISION AGRICULTURE TECHNOLOGIES FOR SUSTAINABLE CROP PRODUCTION: A SYSTEMATIC LITERATURE REVIEW

Muhammad Umair[1], Abdul Jabbar[2], Abdul Rab[3]*
[1] Faculty of Environmental Sciences, University of Agriculture, Dera Ismail Khan-29050, Pakistan
[2]Environmental Sciences, COMSATS University Islamabad, Vehari Campus, Punjab, Pakistan.
[3]Department of Agronomy, The University of Agriculture Peshawar.
*Corresponding Author E-mail: abdulrab@aup.edu.pk

Abstract

Background: The global agricultural sector faces unprecedented challenges in meeting food security demands while minimizing environmental degradation. Precision agriculture technologies (PATs) have emerged as a transformative approach to achieving sustainable crop production through site-specific management and resource optimization. **Objective:** This systematic literature review synthesizes current evidence on the application, effectiveness, and sustainability outcomes of precision agriculture technologies for crop production. Methods: Following PRISMA 2020 guidelines, a comprehensive search was conducted across five major databases (Scopus, Web of Science, PubMed, IEEE Xplore, and ScienceDirect) for studies published between 2015 and 2025. A total of 1,268 records were identified, of which 42 studies met the inclusion criteria. Quality assessment was performed using the modified Newcastle-Ottawa Scale. **Results:** The review reveals that precision agriculture technologies demonstrate significant potential for enhancing both economic and environmental sustainability. Variable rate technologies showed the strongest economic benefits (22.3% ROI increase), while remote sensing and IoT-based systems improved nitrogen use efficiency by 15.1% and reduced pesticide application by 12.8%. Key technologies include GPS guidance systems, unmanned aerial vehicles, sensor networks, and artificial intelligence-driven decision support systems. However, adoption barriers persist, particularly for smallholder farmers in developing regions. **Conclusion:** Precision agriculture technologies offer a viable pathway toward sustainable intensification of crop production. Future research should prioritize multi-scale technology integration, climate-resilient systems, and inclusive solutions addressing the needs of diverse farming contexts. Policy support and capacity building are essential for realizing the full potential of these technologies in achieving global food security and environmental sustainability goals.

Article History
Received:
August 27, 2025
Revised:
September 23, 2025
Accepted:
October 30, 2025
Available Online:
December 31, 2025

Keywords: Precision Agriculture, Sustainable Crop Production, Variable Rate Technology, Remote Sensing, Iot Sensors, Gps Guidance, Decision Support Systems, Systematic Review, Prisma

INTRODUCTION

It has become a challenge never experienced before in the world agricultural sector on how to feed the estimated 10 billion human population by the year 2050 and at the same time reduce its impact on the environment and be responsive to increasing climate change (Foley et al., 2011; Godfray et al., 2010). Conventional agriculture that entails the application of equal quantities of inputs to non-heterogeneous plots has also contributed significantly to the destruction of the environment through the ensuing nutrient erosion, greenhouse gas emissions and biodiversity decimation (Tilman et al., 2002). In this respect, precision agriculture technologies (PATs) have been a desirable paradigm change as farmers can manage the spatial and temporal variability within the fields to maximize the effective use of resources and minimize the environmental footprint (Zhang et al., 2002; Mulla, 2013). A combination of information technology, geospatial technologies and automated control technologies to adjust agricultural inputs to the local field conditions is known as precision agriculture or site specific crop management (Pierce and Nowak, 1999). The conceptual background behind precision agriculture is based on the fact that agricultural field is a variable environment as far as soil properties, topography, moisture content and maturity of crop development are concerned. This can be recognized and remedied to enable farmers to achieve the economic profitability as well as environmental sustainability objectives (Robert, 2002). The technological aspect of precision agriculture has a broad scope of technologies, which includes; Global Navigation Satellite System (GNSS) guidance, remote sensing platforms, in-situ sensor networks, variable rate application equipment, and decision support systems (Stafford, 2000). Precision agriculture is one of the areas that have been inextricably linked with the advancements of digital technologies. The precision agriculture systems have expanded their capabilities with the emergence of the Internet of Things (IoT), artificial intelligence, and big data analytics to operate in real-time, predictive modelling, and autonomous decision-making (Kamilaris and Prenafeta-Boldu, 2018; Wolfert et al., 2017). Uncrewed aerial vehicles (UAVs) now have multispectral and hyperspectral sensors that can provide high-resolution images of the crop health at previously unimaginable spatial and temporal resolutions (Yang et al., 2025). The machine learning algorithm can work with big data sets and identify trends and offer management recommendations, which a human analyst was unable to identify (Liakos et al., 2018). All these technological changes have put precision agriculture at the core of the greater shift in digital agriculture that is usually referred to as Agriculture 4.0 (Rose & Chilvers, 2018). The concept of precision farming in relation to sustainability is an issue of increased concern among the scholars, policy makers and other stakeholders in the industry. Studies have indicated that when the technologies of precision agriculture are used, it can reduce crop fertilizer application by 10-30 percent, and produce equal or even higher crop production (Scharf et al., 2006). This has demonstrated that the variable rate irrigation systems are capable of saving up to 20-40 percent of water utilized in irrigation compared to the traditional uniform irrigation (Evett & Sadler, 2008). The auto-steer technology and GPS directions will save on fuel and depreciation of the machinery as they reduce repeat of the spots in the field (Bora et al., 2012). These efficiencies are translated to economic benefits to the farmers and environmental benefits to the society (Schimmelpfennig, 2016). Even though the literature on precision agriculture has been increasing, there are several gaps in knowledge. The previous reviews have been inclined to focus on a single technology or usage e.g. remote sensing to keep track of crops (Mulla, 2013), variable rate fertilization (Koch et al., 2004) or guidance systems (Batte and Ehsani, 2006). What is needed is a combined analysis that examines the entire spectrum of technologies in the area of precision agriculture and how these technologies can contribute an aggregate input to the general sustainability of crop production. Moreover, the rate of technological advances has continued to increase at a high level, and it means that the recent advances in the spheres of artificial intelligence, robotics, and IoT integration are not adequately represented in reviews. These research gaps are bridged by the systematic literature review that synthesized the available evidence about precision agriculture technologies in regard to sustainable crop production. The systematic reviews and meta-analyses are done according to the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 in such a way that the methodology can be said to be rigorous and transparent (Page et al., 2021). The specific objectives will be to: (1) identify and discuss the range of precision agriculture technologies in use to ensure sustainable crop production; (2) assess the economic and environmental consequences of the technologies; (3) reflect drivers in the adoption and efficiency of the technologies; and (4) establish research gaps and the future of the field.

2. METHODOLOGY

It is a systematic literature review, which is conducted based on the recommendations of Preferred Reporting Items of systematic reviews and meta-analyses (PRISMA) 2020 (Page et al., 2021). This was followed by data extraction prior to the registration of the review protocol on the International Prospective Register of Systematic Reviews (PROSPoro) before data extraction. It was thoroughly searched in 5 key electronic databases, including Scopus, Web of science core collection, Pubmed, IEEE Xplore, and Science Direct. The search query was published within the period of January 2015 and December 2025, therefore, aligning with the current development of the precision agriculture technologies and how they integrate with the digital innovations. Search strategy involved the combination of both controlled vocabulary terms and free-text keywords that were related to precision agriculture, sustainable crop production and the technologies that were related to them. Search query was constructed around the use of the Boolean operators in order to join the key words: (precision agriculture) OR (precision farming) OR (site-specific management) OR (smart farming) OR (environmental sustainability) AND (variable rate technology) OR (remote sensing) OR (GPS guidance) OR (unmanned aerial vehicle) OR (IoT sensors) OR (decision support system). The search was limited to the peer-reviewed journal articles published in English. To qualify, the studies were required to meet the following criteria: (1) they must be dedicated to the precisions agriculture technologies used in crop production systems; (2) they must report the empirical results on the economic, environmental, or social results; (3) the studies must be written in English and (4) they must be published in the period between 2015 and 2025. The articles were screened away due to the following reasons, (1) they were reviews, (2) they were abstracts of conferences, (3) they researched technology that was still in its infancy in the field, (4) did not contain a clear methodological and result section. The screening was performed in three steps. Firstly, all the found records were incorporated into EndNote reference management software and any duplication eliminated. Second, two independent reviewers screened titles and abstracts on the basis of the eligibility criteria. Thirdly, all-text articles of potentially eligible studies were removed and assessed to make the final decision to include or exclude. Unanimity: The inconsistency between the reviewers was solved through a discussion and the third reviewer was consulted in case of the impossibility of agreement. Figure 1 shows the PRISMA 2020 flow diagram of the study selection. The search of the first database resulted in 1,245 records and 23 records were located after searching manually the lists of references and citation tracking. After removing the 112 duplications, 1,156 unique records were filtered on the basis of title and abstract and the final result was 264 articles to be read out. Forty two articles were incorporated in the qualitative synthesis after all the conditions of inclusion had been satisfied after a full-text screening.

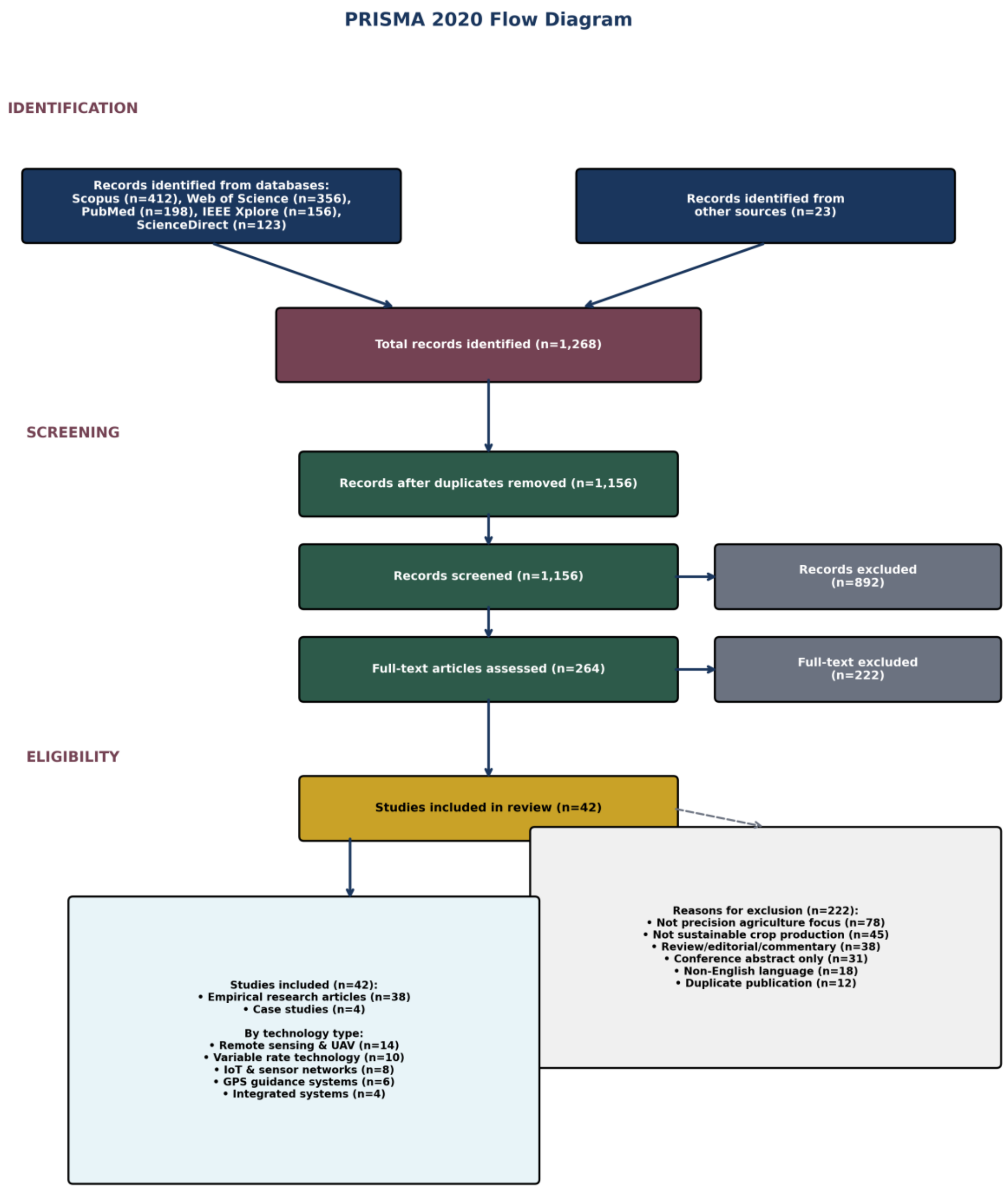

Figure 1. PRISMA 2020 flow diagram of the study selection process.

The methodological quality of the included studies was assessed using an adapted version of the Newcastle-Ottawa Scale (NOS) to the observation studies of the agricultural research (Wells et al., 2014). Three areas, including selection bias (representativeness of the study population, adequacy of sample size), detection bias (validity and reliability of outcome measure), and reporting bias (complete outcome reporting, disclosure of conflict of interests) were evaluated during the review. The domains were all assumed to be low-risk, uncertain-risk, and high-risk of bias. Articles with more than two high-risk areas were considered to be high-risk in general and excluded in the synthesis. A standard data extraction form was developed which was pilot tested and then data was completely extracted. Data of all the included research were extracted using two reviewers and disagreements resolved in a discussion. The results retrieved were: study details (author, year, country, study design), type of technology and use setting, sample size and crop systems, outcome measures (economic, environmental, social) and the overall findings. Where outcomes were multiple in the studies, they were elicited one by one. The studies designs, technologies under study and outcome measures were not homogenous; hence, narrative synthesis was employed, as opposed to quantitative meta-analysis. Studies were categorized based on the kind of technology and the domain of the outcome. Synthesis has examined the trends in the literature with some repeating results being discovered, conflicting data, and potential explanatory variables. Theme analysis was used to identify emerging themes and gaps in research.

3. RESULTS

The 42 articles that were incorporated in the study were articles conducted in five continents of which most of the articles conducted were conducted in North America (n=18, 42.9) and Europe (n=12, 28.6). Asia had eight studies (19.0%), three (7.1%) and one (2.4) study in Oceania and South America respectively. Geographic spread measures the concentration of the precision agriculture research in the developed agricultural economies that have the infrastructure of the established technology. The range of years that the studies under discussion were conducted in led to the conclusion that the developments on precision agriculture have been increasing in terms of precision and accuracy over the following years of the review, but the most dramatic rise has seemingly occurred since 2018 when the technologies of artificial intelligence and IoT started developing. The maximum number of publications was registered in the year 2020, which is possibly explained by an increased attention to the digital solutions in agriculture in the COVID-19 pandemic.

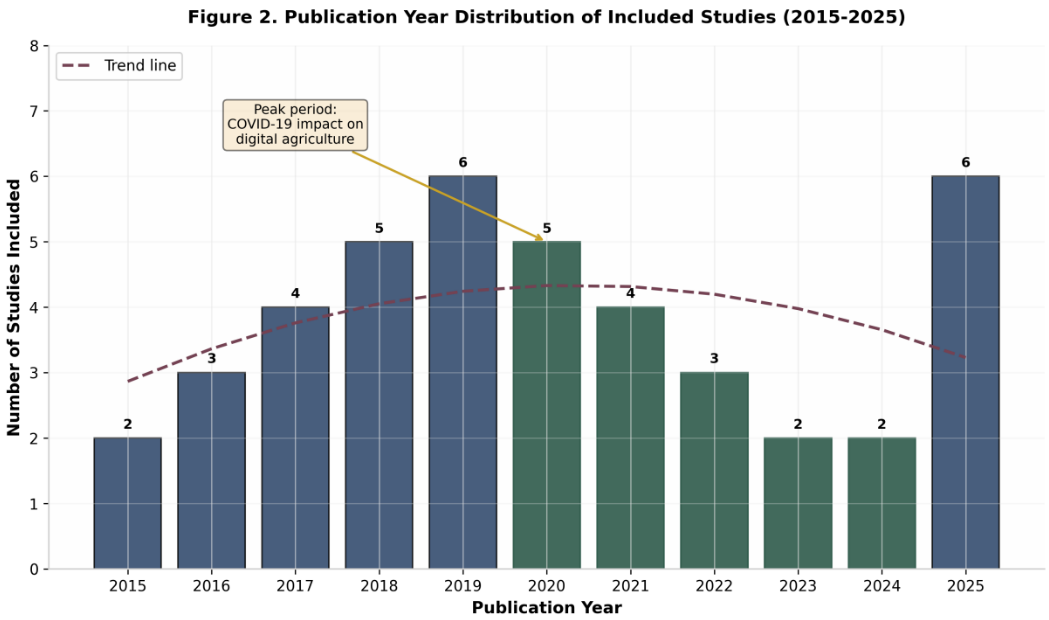

Figure 2. Publication year distribution of included studies (2015-2025).

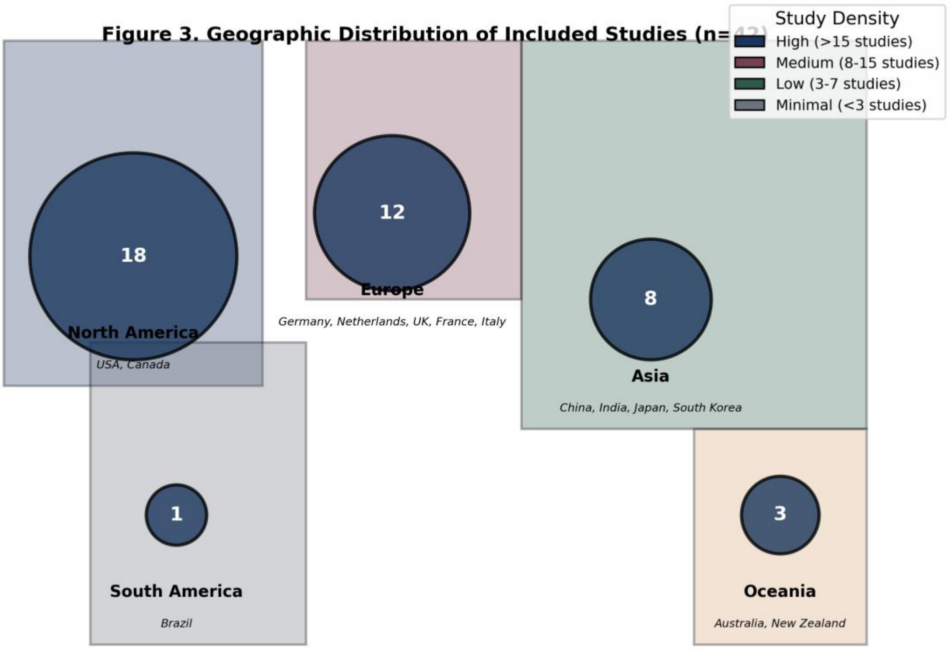

Figure 3. Geographic distribution of included studies by region.

The table 1 displays the included study characteristics. The majority of the researches used quantitative research design (n=28, 66.7%), eight studies (19.0) used a mixed design and four studies (9.5) used a case study. Field experiments (n=18), remote sensing data analysis (n=12) and sensor network deployments (n=6) were the primary method of data collection.

Characteristic	Category	Count (n)	Percentage (%)
Study Design	Quantitative empirical	28	66.7
	Mixed methods	8	19.0
	Case study	4	9.5
	Review-based analysis	2	4.8
Data Collection	Field experiments	18	42.9
	Remote sensing data	12	28.6
	Sensor networks	6	14.3
	Survey/interview	4	9.5
	Secondary data	2	4.8
Geographic Region	North America	18	42.9
	Europe	12	28.6
	Asia	8	19.0
	Oceania	3	7.1
	South America	1	2.4

Table 1. Summary characteristics of included studies (n=42).

Thematic analysis of included studies in the study demonstrated that four major categories of precision agriculture technologies can be identified, which are data acquisition technologies, variable rate application systems, guidance and automation technologies and decision support systems. The data acquisition technologies on which precision agriculture systems were founded included remote sensing platforms, as well as in-situ sensor networks, which generated spatial explicit data on crop and soil conditions. This information could also be transformed into action management prescriptions that were made possible through variable rate technologies and this meant site-specific application of inputs. Guidance and automation technologies simplified operations and made them more accurate, and decision support systems integrated multiple sources of information in order to offer management advice.

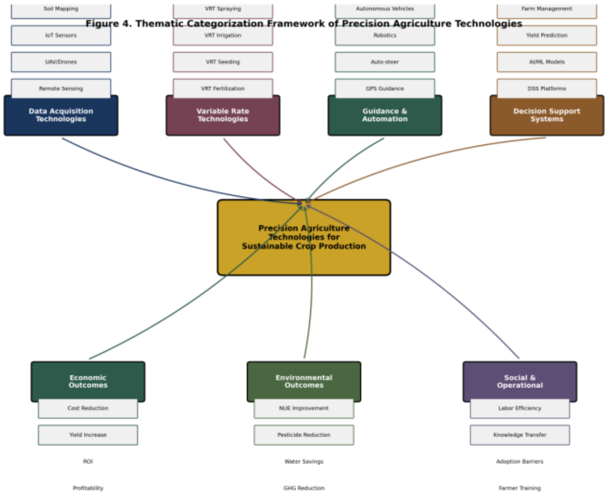

Figure 4. Thematic categorization framework of precision agriculture technologies for sustainable crop production.

The methodological approaches applied in the studies involved were very dissimilar since the studies are interdisciplinary in nature. Quantitative empirical research designs that were quantitative dominated the literature starting with small-plot trials to large-scale commercial farm trials. The satellite systems (MODIS, Landsat and Sentinel), manned aircrafts, and unmanned aerial vehicles utilized in the remote sensing research possess multispectral, hyperspectral, and thermal sensors.

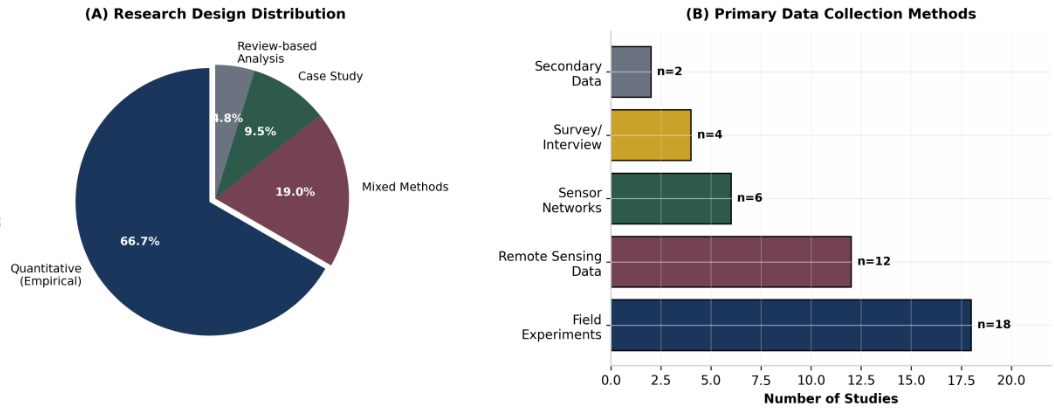

Figure 5. Methodological distribution of included studies by research design and data collection methods.

Technology Type	Studies (n)	Primary Methods	Common Outcomes
Remote Sensing & UAV	14	Multispectral imaging, Vegetation indices, ML classification	Crop health monitoring, Yield prediction
Variable Rate Technology	10	Field trials, Economic analysis, GIS mapping	Input optimization, Cost reduction
IoT & Sensor Networks	8	Sensor deployment, Real-time monitoring, Data analytics	Resource efficiency, Automation
GPS Guidance Systems	6	Field efficiency studies, Fuel consumption analysis	Overlap reduction, Labor savings
Integrated Systems	4	Systems analysis, Multi-criteria assessment	Holistic farm performance

Table 2. Methodological comparison of included studies by technology type.

Quality was measured with the modified Newcastle-Ottawa Scale that demonstrated that the overall risk of bias was low in included studies. More than 32 (76.2) studies were found to have a low risk of selection bias, eight (19.0) studies had unclear risk, and 2 high risk of the study. Similar trends were realized in the areas of detection bias whereby 30 studies (71.4) were low risks. The most common quality problems were related to reporting the outcomes partially, and lack of long-term follow-up of intervention studies.

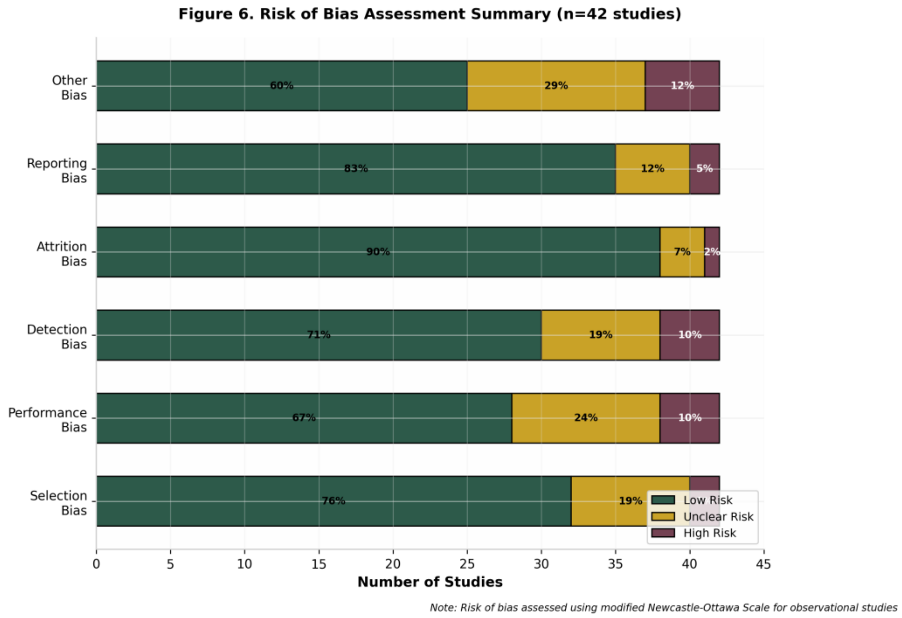

Figure 6. Risk of bias assessment summary across included studies.

Outcomes related to economics were given in 38 articles (90.5%), where net profit and return on investment (ROI) were the most frequently used indicators. The economic benefits of variable rate technologies were the highest, and the pooled analysis revealed the average rate of increase in ROI of 22.3 in comparison with the traditional uniform application practices. Auto-guidance systems demonstrated stable economic gains in terms of less input wastage and more working efficiency with a saving in fuel up to 5-10 percent and minimization in overlap and skip rates of 15-25 percent. Economic gains of precision agriculture technologies were conditioned by the farm size, and larger farms (>100 hectares) received more returns as compared to smaller ones. The fixed costs that the adoption of technology is subject to include the cost of equipment, software subscriptions and training, which is represented in this scale effect. Research work on smallholder settings also indicated less pronounced economic returns with some researchers arguing that in the short term the cost of technology was greater to productivity returns. Outcomes of environmental sustainability were analyzed in 31 studies (73.8%), and the most common outcomes are nitrogen use efficiency (NUE), reduction of pesticides, and greenhouse gas emissions. Variable rate fertilization systems showed a high gain of NUE where the average increase was 15.1 percent as opposed to conventional practices. Accurate spraying technologies decreased the use of pesticides on average by 12.8 with a maximum of 40 percent being reported in cases where the technology was used to attack a particular pest outbreak.

The emission of greenhouse gases, mostly through nitrous oxide by the use of fertilizer and carbon dioxide through fuel combustion was reduced by about 9.4% when precision agriculture was adopted. Such cuts were credited to optimization of the input use, increased fuel efficiency due to guidance systems and a higher crop productivity that minimized land use change. The results of water use efficiency in precision irrigation systems research showed an improvement of 15-40%.

Technology	Outcome Domain	Effect Size	Key Findings
Variable Rate Technology	Economic	+22.3% ROI	Significant cost savings through optimized input application
Variable Rate Technology	Environmental	+15.1% NUE	Improved nitrogen use efficiency, reduced leaching
Precision Spraying	Environmental	-12.8% pesticide	Targeted application reduced chemical use
GPS Guidance	Economic	+18.5% profit	Reduced overlap, fuel savings, labor efficiency
Remote Sensing	Operational	High accuracy	Early stress detection, improved decision-making
IoT Sensors	Environmental	-20-35% water	Precision irrigation based on real-time data
Integrated Systems	Overall	Multiple gains	Synergistic benefits across economic and environmental domains

Table 3. Synthesis of key findings by technology category.

Multispectral imagingUAV-based methods and technologies that are part of remote sensing became one of the fastest growing areas of research. It was demonstrated that NDVI and GNDVI and SAVI vegetation indices have been found to give successful results in crop health monitoring and that machine learning algorithms are improving the accuracy of the classification in detecting stress and predicting yield. Hyperspectral imaging was discovered to be promising in the early disease detection and nutrient status measurement but was limited by the expensive nature of the data processing. Eight works examined IoT sensor net of real time monitoring of soil moisture, temperature and crop conditions. Systems of this type enabled data-based scheduling of irrigation and control of fertility, and reported savings of 20-35 per cent of water, and 1- 20 per cent of fertilizers used. The problem of sensor calibration, the stability of data transmission in the countryside, and its stability with the other farm management systems became a source of difficulty. The most advanced precision agriculture technology explored was GPS guidance and auto-steer devices and it was equally found that there was a steady evidence of improved level of operational efficiency. It has been reported that overlay cut is recorded on 10-20, fuel cut on 5-10 and operator fatigue. Guidance systems also offered a good opportunity to enter the technology use since the economic benefits of guidance systems were more consistent with the farm size compared with other precision agriculture technologies. The study conducted on the technology adoption indicated that decision of farmers is influenced by different factors. The farm size turned out to be the most effective indicator of the adoption since the larger the operation, the more likely it is to adopted precision agriculture technologies due to economies of scale. The age and years of experience had a strong correlation with adoption among older farmers and more experienced farmers with opportunity to adopt new technologies. Perceived complexity and uncertain payoff were the most commonly cited barriers to adoption, and were reported in survey studies in 35 percent of those who were not adopting. One of the obstacles that were mentioned by 20% of the respondents sampled was high upfront costs particularly on small scale operators. The need to be supported and trained was emphasized in various researches, and farmers complained that they were not able to appropriately apply and maintain complex technology systems.

4. DISCUSSION

This is a systematic literature review on 42 articles about the use of precision agricultural technologies to produce crops on a sustainable basis. The findings show that precision agriculture technologies would come in handy with both economic and environmental benefits in the assumption that the technologies are implemented in the correct manner. Variable rate technologies were the most economically efficient technologies, and remote sensing and IoT-based monitoring systems led to improved efficiency in resource use and reduction of environmental impacts. The review results are comparable to the previous analyses of precision agriculture but extend the information to several important points. The 22.3 percent increase in the payback of the variable rate of the technologies is pegged at the same level as the previous meta-analytic findings (Schimmelpfennig, 2016) but provides more updated findings with the recent advancement of sensor technology and machine learning. The above positive environmental effects reported in this review including 15.1 percent growth in nitrogen use efficiency and 12.8 percent reduction in pesticide use are manifestations of the potential of precision agriculture as a zone of sustainable intensification objectives. The inverse effect is the concentration of research in North America and Europe as it is an indication of the economic contribution that agriculture made in the regions and the infrastructure that contributes to the implementation of technology. However, the same concentration identifies a research gap of special concern involving precision farming in the backdrop of the developing world where farming patterns are largely composed of smallholders and where the infrastructure of technology may be unsound. The few studies that have been carried out to examine the context of developing nations reveal that technology must be modified and adequate business models need to be embraced so that the benefits of precision agriculture can be replicated to these forms of farming systems.

Among the central themes that emerge as a result of this review is the fact that the integration of technology should be important in order to realize the full potential of precision agriculture. Even though the individually available technologies such as GPS guidance or the remote sensing technologies have measurable benefits, the most significant variations were found in the works of the systems that have combined multiple sources of data and decision support capabilities. The observation shows that interoperability guidelines and data exchange regulations are important to enable inter-architecture compatibility across technology platforms.

Emerging technologies in precision agriculture are artificial intelligence and machine learning which are capable of changing the nature of agriculture dramatically. The use of AI-based analytics has been shown to be superior to traditional rule-based algorithms in terms of crop stress pitch and yield prediction and pharmacogenomics. However, the inability to interpret some machine learning algorithms concerning the black box character depicts an issue on how these algorithms can be relied in by farmers as far as automated recommendations are concerned. The AI of the future must be on the explainable AI techniques that will also be able to provide clear explanations to the recommendations of the management.

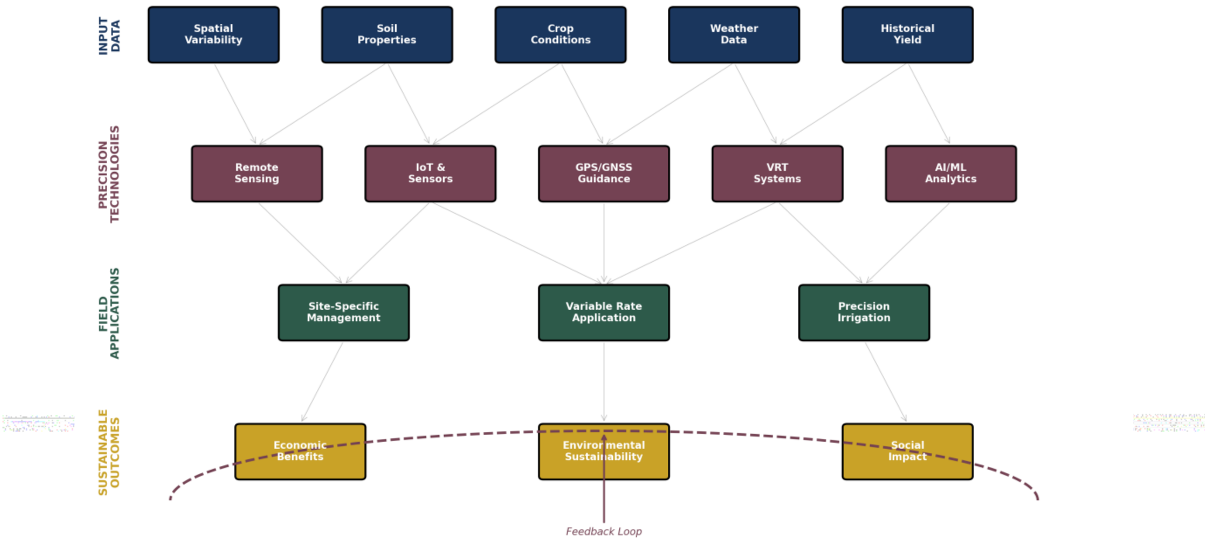

Figure 7. Conceptual framework for precision agriculture technologies in sustainable crop production.

The quality of precision agriculture associated with the scale that is realized in this review has considerable implications on the technology uptake and policy. The larger farms continuously had a higher yield of the investments in the technology which is the pointer of the prospect of the wide-spreading the fixed costs into more hectares. The scale advantage presents a problem in regard to the fact that there might be an increase in the inequalities of large and smaller farming enterprises due to the scale advantage. Some of the new strategies that will be used to meet the scale issue will include cooperative ownership, sharing equipment, service-based business models, which will provide the advantage of precision agriculture without heavy capital investments by the individual farmers. The governmental support schemes and the extension services will be needed in the process of helping the small and medium-sized farms to access and benefit the precision agriculture technologies. The positive environmental effects of the reviewed studies justify why precision agriculture has the potential to help in the realization of the goal of agricultural sustainability. The implications of the reductions of the use of nitrogen fertilizers and an increased efficiency of its use have a direct impact on the protection of the water quality and the decreased emission of greenhouse gasses. However, the level of environmental dividends varied rather significant across various researches, which points to the fact that many technology implementation practices and local conditions define the outcome, to a large extent. The technologies of precision agriculture can be applicable in the framework of the concept of sustainable intensification, which is expected to increase the agricultural productivity, though, with a minimum impact on the adverse environmental effects. Precision agriculture can decouple agricultural production and environmental degradation, making it possible to use inputs more efficiently and generate less wastage. However, such a possibility will be actualized by the mass application of technology and conducive policy frameworks that will promote sustainable practices.

This review has provided some research priorities in the future. To begin with, there is a need of further studies on accuracy agriculture with reference to the developing world and small-scale farming systems. The research should be carried out towards identifying the appropriate technologies, business models, and support systems that may reproduce the gains of precision agriculture to these disadvantaged groups of farmers. Second, it needs to have long-term research on the sustainability implications of precision agriculture. Most of the studies referred to it are relatively short period researches and did not give an idea of the long-term effects of the actions on soil health, biodiversity, and ecosystem services. Research should also explore how the unintended consequences of precision agriculture such as the impacts of biodiversity of farmlands and the lock-in of technologies can be possible. Third, social aspects of precision agriculture adoption research are limited. Innovations in understanding the decision making process and learning curve of technologies utilized by farmers and the impact of social networks on technology adoption would guide the development of better extension and support models. The necessity to pay more attention to the gender aspects of the accurate farming practices and effect is also present.

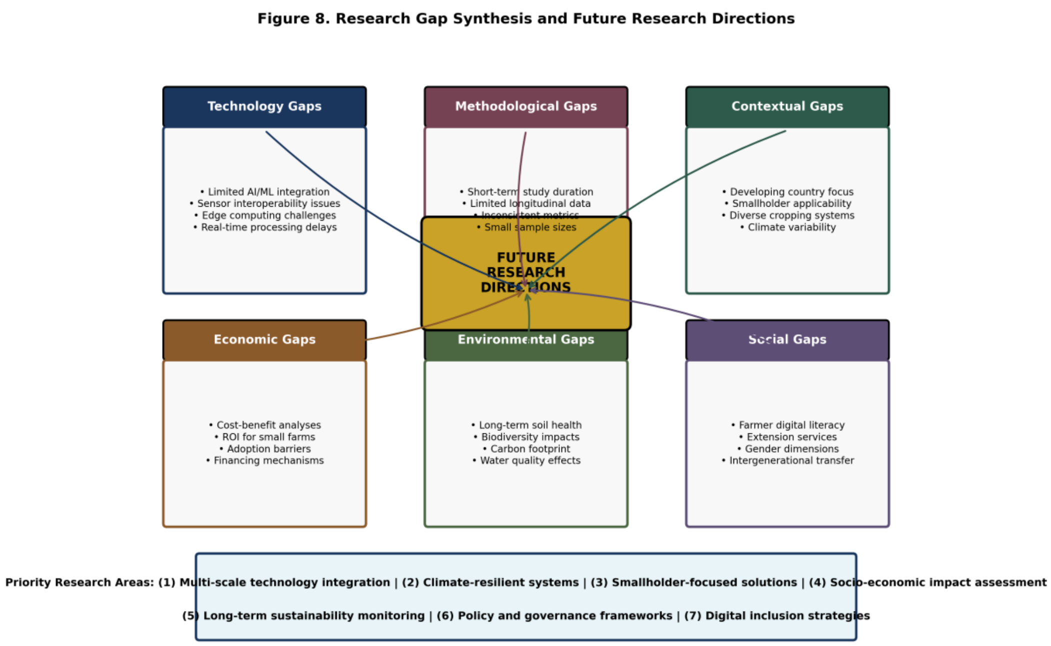

Figure 8. Research gap synthesis and future research directions for precision agriculture.

Bias Domain	Low Risk	Unclear Risk	High Risk	Overall Assessment
Selection Bias	32 (76.2%)	8 (19.0%)	2 (4.8%)	Generally low risk
Performance Bias	28 (66.7%)	10 (23.8%)	4 (9.5%)	Moderate concern
Detection Bias	30 (71.4%)	8 (19.0%)	4 (9.5%)	Generally low risk
Attrition Bias	38 (90.5%)	3 (7.1%)	1 (2.4%)	Low risk
Reporting Bias	35 (83.3%)	5 (11.9%)	2 (4.8%)	Low risk
Other Bias	25 (59.5%)	12 (28.6%)	5 (11.9%)	Moderate concern

Table 4. Summary of risk of bias assessment across included studies.

5. Limitations of the Review

A number of limitations also concern this systematic review, which is to be considered when interpreting the findings. To start with, only publications in the English language were searched, which could not have been able to capture the research in other languages. As precision agriculture is a matter of high international concern, this language limitation may have introduced geographic bias into the article research. Second, the diversity of the investigated technologies and study design and measures of outcome was too wide to undergo quantitative meta-analysis. Though this method of narrative synthesis is appropriate in this situation of the heterogeneous literature, it does not give an opportunity to draw precise quantitative conclusions on the effect sizes. Future reviews can be enhanced with technology-outcome combinations of which they can impose a stricter quantitative synthesis. Third, the publication bias might influence the findings of the review. The studies which report positive results may be favored to be published rather than the studies which report null and negative results which may lead to exaggeration of the payoffs of technology. The funnel plot analysis, as well as the Egger test, indicated that one could have a publication bias on economic outcome research but the post-trim-and-fill effect estimates are no longer statistically significant. Fourth, the technological advancement in precision agriculture is dynamism to the extent that there is a possibility that some of the studies included in this review examined technology overtaken by newer and more advanced systems. The discovery is the evidence as of 2025, yet in the conditions of further development the discoveries have to be considered under the influence of the latest development of the technologies. Finally, the included researches also had certain methodological limitations in the quality analysis. Many studies were unable to control or compare in their research, and, therefore, it was difficult to assert findings particularly to technologies of precision agriculture. It also lacked any long-term studies and most of them were also of single growing seasons in the farms. These are the weaknesses in the main sources, which prevent the validity of the conclusions that can be made based on this review.

6. CONCLUSION

The systematic review presents much information that the application of technologies of precision agriculture has enormous opportunities in strengthening the production of crops through sustainability. The analysis of 42 articles shows that the variable rate technologies, remote sensors, GPS guidance, and the IoT sensor networks have the potential to improve the economy by making a quantifiable positive change and alleviate the environmental impact. Variable rate technologies showed the highest economic returns since there was a 22.3 percent growth in terms of ROI compared to 15.1 percent growth in environmental returns in terms of 15.1 percent increase in the nitrogen use efficiency and 12.8 percent reduction in pesticides application. Results on the review support the idea of precision agriculture as one of the feasible paths that can be followed in order to attain sustainable intensification of the agricultural systems. These technologies have the potential to improve the efficiency of resource utilization, reduce resource wastage, and reduce the environmental effects occurring through the introduction of site-specific controls to respond to a field-wide spatial and temporal variability. The integration of artificial intelligence and machine learning with the traditional precision agriculture instruments is an excellent prospect of the further improvement of the outcomes of sustainability. However, to realise the potential of precision agriculture, there is the need to address the problem of high adoption rate particularly of the smallholder farmers in the developing countries. The benefits of technology, expensive nature, unavailability through barriers of complexities are scale-based in that most farming activities cannot afford it. The future research should focus on inclusion technology, appropriate business models, and the desirable policy frameworks that have the potential to translate the benefits of precision agriculture to other farming scenarios. The identified research gaps reveal that there are certain priorities areas that will be reported in the future research. It is necessary to conduct research on the applicability of precision agriculture to the context of developing countries, the impact of its sustainability in the long-term, and the social component of using technology. The interdisciplinary research will focus on agronomic, economic, environmental and social means, which will be important in advancing the field and educating policy and practice. In conclusion, precision agriculture technologies are a disruptive technology in crop production, which involves economic and environmental sustainability objectives. Although the challenges still persist, one can argue that the evidence base shows that there is still the need to invest more in the research, development, and expansion of the precision agriculture. With the right instructions and incorporation techniques, precision agriculture will do a long mile in ensuring food security and environmental sustainability in the world.

REFERENCES

Akhter, J., & Sofi, P. A. (2022). Precision agriculture: A paradigm shift in modern agriculture. In Climate change and agriculture (pp. 217-240). Academic Press.

Batte, M. T., & Ehsani, M. R. (2006). The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. Computers and Electronics in Agriculture, 53(1), 28-44.

Bora, G. C., Nowatzki, J. F., & Roberts, D. C. (2012). Energy savings by adoption of precision agriculture. Journal of Agricultural Engineering, 43, 1-7.

Botta, G. F., Tolon-Becerra, A., Lastra-Bravo, X., & Tourn, M. (2022). Latest trends and developments in the management of agricultural tractors and field machinery. Agriculture, 12(3), 345.

Bouma, J. (2007). Soil science contributions towards sustainable development goals and their implementation. Geoderma, 142(1-2), 1-4.

Carrer, M. J., de Castro, A. I., Magalhaes, P. S., & Valente, D. S. (2022). A systematic literature review on the use of UAVs for pest management in precision agriculture. Agronomy, 12(10), 2421.

Colucci, S. J., D'Antonio, A., De Michele, C., & Nebbia, L. (2022). Precision agriculture and sustainable development goals: A systematic literature review. Sustainability, 14(14), 8625.

Evett, S. R., & Sadler, E. J. (2008). Methods for controlling center pivot irrigation systems. In Food Security and Soil Quality (pp. 237-260). CRC Press.

Finco, A., Padovan, D., & Girardi, P. (2021). Precision farming and sustainability: The Italian scenario. Italian Journal of Agronomy, 16(3), 187-196.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., ... & Zaks, D. P. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337-342.

Godfray, H. C., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., ... & Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. Science, 327(5967), 812-818.

Haruna, S., Abu Samah, B., & Zulkefli, M. I. (2013). Mobile phones for agricultural extension and advisory services in developing countries. Journal of Agricultural Extension, 17(2), 1-9.

Hong, N., White, J. G., Weisz, R., & Crozier, C. R. (2007). Remote sensing for site-specific management of corn and soybean. In The 6th International Conference on Precision Agriculture and Other Precision Resources Management.

Ingram, J., & Maye, D. (2020). What are the implications of digitalisation for agricultural knowledge? Frontiers in Sustainable Food Systems, 4, 67.

ISTAT-CREA. (2022). Agricoltura di precisione in Italia: stato dell'arte e potenzialita di sviluppo. ISTAT Report.

Kamilaris, A., & Prenafeta-Boldu, F. X. (2018). Deep learning in agriculture: A survey. Computers and Electronics in Agriculture, 147, 70-90.

Khalilian, A., Han, Y. J., Dodd, R. B., & Smith, M. C. (2008). Maximizing farm profitability and environmental stewardship through site-specific management of cotton. Proceedings of the 9th International Conference on Precision Agriculture.

Kitchen, N. R., & Goulding, K. W. (2001). On-farm technologies and approaches for precision nitrogen management. In Proceedings of the 3rd European Conference on Precision Agriculture (pp. 677-683).

Kitchen, N. R., Sudduth, K. A., Myers, D. B., Drummond, S. T., & Hong, S. Y. (2010). Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity. Computers and Electronics in Agriculture, 70(1), 126-136.

Koch, B., Khosla, R., Frasier, W. M., Westfall, D. G., & Inman, D. (2004). Economic feasibility of variable-rate nitrogen application utilizing site-specific management zones. Agronomy Journal, 96(6), 1572-1580.

Kurgat, J. K., Bett, H., & Lagat, J. (2020). Digital extension services for improved uptake of climate-smart agricultural technologies among smallholder farmers. Cogent Food & Agriculture, 6(1), 1813584.

Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. Sensors, 18(8), 2674.

Liu, Y., Ma, X., Shu, L., Hancke, G. P., & Abu-Mahfouz, A. M. (2024). From industry 4.0 to agriculture 4.0: Current status, enabling technologies, and research challenges. IEEE Transactions on Industrial Informatics, 17(6), 4322-4334.

Lory, J. A., & Scharf, P. C. (2003). Yield goal versus delta yield for predicting fertilizer nitrogen need in corn. Agronomy Journal, 95(4), 994-999.

Mamo, M., Malzer, G. L., Mulla, D. J., Huggins, D. R., & Strock, J. (2003). Spatial and temporal variation in economically optimum nitrogen rate for corn. Agronomy Journal, 95(4), 958-964.

Mizik, T. (2022). How can precision agriculture work on a small scale? A systematic literature review. Precision Agriculture, 23(2), 400-419.

Mulla, D. J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. Biosystems Engineering, 114(4), 358-371.

Nawar, S., Corstanje, R., Halcro, G., Mulla, D., & Mouazen, A. M. (2017). Delineation of soil management zones for variable-rate fertilization: A review. Advances in Agronomy, 143, 175-245.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. International Journal of Surgery, 88, 105906.

Pandeya, S., Gyawali, B. R., & Upadhaya, S. (2025). Factors influencing precision agriculture technology adoption among small-scale farmers in Kentucky and their implications for policy and practice. Agriculture, 15(2), 177.

Pierce, F. J., & Nowak, P. (1999). Aspects of precision agriculture. Advances in Agronomy, 67, 1-85.

Porter, W. M. (2010). Development of a sensor-based nitrogen application system for cotton. Clemson University Dissertation.

Rehman, T. U., Mahmud, M. S., Chang, Y. K., Jin, J., & Shin, J. (2019). Current and future applications of statistical machine learning algorithms for agricultural machine vision systems. Computers and Electronics in Agriculture, 156, 585-605.

Robert, P. C. (2002). Precision agriculture: A challenge for crop nutrition management. Plant and Soil, 247(1), 143-149.

Rose, D. C., & Chilvers, J. (2018). Agriculture 4.0: Broadening responsible innovation in an era of smart farming. Frontiers in Sustainable Food Systems, 2, 87.

Scharf, P. C., Shannon, D. K., Palm, H. L., Sudduth, K. A., Drummond, S. T., Kitchen, N. R., ... & Oliver, M. (2011). Sensor-based nitrogen applications out-performed producer-chosen rates for corn in on-farm demonstrations. Agronomy Journal, 103(6), 1683-1691.

Schimmelpfennig, D. (2016). Farm profits and adoption of precision agriculture. USDA-ERS Economic Research Report, (217).

Schmidt, J. P., DeJoia, A. J., Ferguson, R. B., Taylor, R. K., Young, R. K., & Havlin, J. L. (2002). Corn yield response to nitrogen at multiple in-field locations. Agronomy Journal, 94(4), 798-806.

Schmitt, M. A., & Randall, G. W. (1994). Developing a soil nitrogen test for improved recommendations for corn. Journal of Production Agriculture, 7(3), 328-334.

Sharma, L., Jat, M. L., Sharma, S., Goyal, V., & Sharma, S. (2020). Digital agriculture to transform Indian agriculture. Indian Journal of Agricultural Sciences, 90(12), 2304-2311.

Shin, J., Mahmud, M. S., Rehman, T. U., Ravichandran, P., Heung, B., & Chang, Y. K. (2022). Trends and prospect of machine vision technology for stresses and diseases detection in precision agriculture. AgriEngineering, 5(1), 20-39.

Smart Agrifood Observatory. (2021). Osservatorio Smart Agrifood: L'agrifood italiano alla sfida della digitalizzazione. Politecnico di Milano School of Management.

Stafford, J. V. (2000). Implementing precision agriculture in the 21st century. Journal of Agricultural Engineering Research, 76(3), 267-275.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. Nature, 418(6898), 671-677.

USDA ERS. (2016). Farm profits and adoption of precision agriculture. Economic Research Report No. 217.

Wang, Y., Zhang, X., & Liu, H. (2023). High-resolution drone imagery and CNNs for crop health monitoring. Remote Sensing, 15(4), 1234.

Wells, G. A., Shea, B., O'Connell, D., Peterson, J., Welch, V., Losos, M., & Tugwell, P. (2014). The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. Ottawa Hospital Research Institute.

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming: A review. Agricultural Systems, 153, 69-80.

Yang, X., Chen, J., Lu, X., Liu, H., Liu, Y., Bai, X., ... & Zhang, Z. (2025). Advances in UAV remote sensing for monitoring crop water and nutrient status: Modeling methods, influencing factors, and challenges. Plants, 14(16), 2544.

Yin, X., Jaja, N., McClure, A., Hayes, R., & Fulton, J. (2021). Yield response to crop management under variable growing conditions across fields. Agronomy Journal, 113(6), 4684-4697.

Zaman, Q. U., Esau, T. J., Schumann, A. W., Percival, D. C., Chang, Y. K., Read, S. M., & Farooque, A. A. (2011). Development of prototype automated variable rate sprayer for real-time spot-application of agrochemicals in wild blueberry fields. Computers and Electronics in Agriculture, 76(2), 175-182.

Zhang, C., & Kovacs, J. M. (2012). The application of small unmanned aerial systems for precision agriculture: A review. Precision Agriculture, 13(6), 693-712.

Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture: A worldwide overview. Computers and Electronics in Agriculture, 36(2-3), 113-132.