Asian Journal of Research in Crop Science

Volume 8, Issue 4, Page 443-453, 2023; Article no.AJRCS.108114
ISSN: 2581-7167

Enhancing Crop Protection and Yield through Precision Agriculture and Integrated Pest Management: A Comprehensive Review

Alhaji Alusine Kebe [a*], Shumaila Hameed [b], Muhammad Sohail Farooq [b], Abu Sufyan [b], Muhammad Babar Malook [c], Sayed Awais [a], Muhammad Riaz [d], Muhammad Waseem [e], Usman Amjad [a] and Nasir Abbas [c]

[a] Department of Agronomy, PMAS arid Agriculture University, Rawalpindi, Pakistan.
[b] Department of Plant Pathology, University of Agriculture, Faisalabad 38000, Pakistan.
[c] Department of Plant Pathology, MNS University of Agriculture Multan, Pakistan.
[d] Department of Plant Pathology, Faculty of Agriculture and Environment, Islamia University of Bahawalpur, Pakistan.
[e] Department of Agronomy, University of Agriculture, Faisalabad 38000, Pakistan.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJRCS/2023/v8i4225

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/108114

Review Article

Received: 03/09/2023
Accepted: 08/11/2023
Published: 17/11/2023

**Corresponding author: E-mail: kebealusinealhaji11@gmail.com;*

ABSTRACT

The increasing global population has intensified the necessity for sustainable and efficient agricultural practices. One promising avenue for meeting this demand is the synergy between Precision Agriculture (PA) and Integrated Pest Management (IPM). This review paper aims to scrutinize the multifaceted relationship between PA and IPM in augmenting crop protection and yield. Utilizing a comprehensive analysis of existing literature, the study elucidates how cutting-edge technologies in PA, such as drone imaging and soil sensor networks, can be harmoniously integrated with IPM strategies. These encompass biological, chemical, and cultural tactics to manage pest populations and mitigate damage, thereby fostering an environment conducive to optimal crop growth. The review identifies that the confluence of PA and IPM not only enhances the efficiency of resource use but also mitigates the environmental footprint of agricultural activities. Moreover, we delve into case studies that demonstrate significant yield improvements and cost reductions, underscoring the economic viability of integrating PA and IPM. The findings highlight the transformative potential of marrying these two domains, suggesting that such integration could be a cornerstone in the future of sustainable agriculture. The paper concludes by outlining research gaps and proposing avenues for future studies, emphasizing the need for multi-disciplinary approaches to fully unlock the potential of this integration.

Keywords: Agronomic crops; crop protection; integrated pest management (IPM); precision agriculture (PA); sustainable agriculture; technological innovations.

1. INTRODUCTION

The urgency to sustainably feed a rapidly growing global population has never been more critical. According to the United Nations, the world population is projected to reach 9.8 billion by 2050, necessitating a 70% increase in food production [1,2]. Consequently, the agricultural sector is experiencing mounting pressure to enhance both productivity and sustainability. In this milieu, two approaches Precision Agriculture (PA) and Integrated Pest Management (IPM) have gained traction as viable solutions for the modernization of farming practices [3,4]. Precision Agriculture employs technology to optimize field-level management in terms of crop farming [5]. Various technologies, such as satellite imaging, Global Positioning System (GPS), and sensor networks, are used to monitor and adjust farming practices tailored to specific conditions within a field [6,7]. On the other hand, Integrated Pest Management is a comprehensive strategy that utilizes multiple techniques, including biological, chemical, and mechanical methods, to control pest populations [8,9].

The integration of Precision Agriculture (PA) and Integrated Pest Management (IPM) offers a promising avenue for simultaneously enhancing crop yields and minimizing environmental impact. Recent studies have demonstrated that the integration of these two approaches leads to more efficient resource utilization, lower pesticide use, and improved crop yield [10,11]. For instance, a study [12] found that utilizing drone technology for pest monitoring in an IPM framework resulted in a 30% reduction in pesticide use. Similarly, [13] observed that soil sensors used for real-time monitoring of soil moisture and nutrient levels could significantly enhance the efficiency of IPM strategies. However, despite the promising benefits, there are significant gaps in the literature regarding the most effective ways to integrate PA and IPM [14]. Most existing studies have focused on either PA or IPM in isolation, without comprehensive insights into how these two can be synergistically combined for maximum impact [15,16]. Moreover, the adoption of PA and IPM in the agricultural sector is still in its nascent stages, and there is a need for more robust empirical studies to validate the efficacy of their integration [17].

This review paper aims to fill these gaps by conducting a thorough examination of existing literature and case studies that explore the integration of PA and IPM. The objective is to provide a comprehensive understanding of how these two revolutionary approaches can be synergistically combined to create a sustainable, productive, and economically viable agricultural system. The paper also identifies the current challenges and limitations, proposing recommendations for future research. As this paper navigates through the complex yet promising landscape of PA and IPM integration, it will also highlight the technological advancements that are driving this synergy. Innovations such as Artificial Intelligence (AI) for predictive modeling, Internet of Things (IoT) for real-time monitoring, and blockchain for traceability are beginning to shape the future of this integration [18,19]. These advancements not only have the potential to revolutionize farming practices but also hold the promise of making agriculture more sustainable and resilient to the challenges posed by climate change [20,21].

The integration of Precision Agriculture and Integrated Pest Management has the potential to significantly enhance crop protection and yield. As the demand for food production continues to surge, it is imperative that the agricultural sector adopts innovative and sustainable approaches. This paper serves as a comprehensive guide, rooted in existing literature, to understand the synergistic relationship between PA and IPM and how it can revolutionize modern agriculture.

1.1 Plan of Study

In the forthcoming sections of this review paper, we aim to provide a multifaceted examination of the integration of Precision Agriculture (PA) and Integrated Pest Management (IPM) within the broader context of sustainable agriculture. Following this introduction, we delve into a comprehensive literature review that surveys key theories, technologies, and empirical findings relevant to both PA and IPM. This sets the stage for a critical discussion on the evolution of crop protection methods, where we contrast traditional, chemical-based, and biological techniques to highlight their respective strengths and limitations. Subsequently, case studies and technological innovations will be explored to offer real-world examples and illuminate the latest advancements in this interdisciplinary field. As we navigate through these topics, we aim to identify current research gaps and suggest avenues for future investigation. The paper culminates with a conclusions section that synthesizes the key findings, their implications for both practice and policy, and their potential to shape future sustainable agricultural practices. Through this structured approach, this review endeavors to offer a nuanced understanding of how the synergistic application of PA and IPM could revolutionize modern agriculture.

2. REVIEW OF LITERATURE

The discourse surrounding sustainable agriculture has been enriched by the emergence of Precision Agriculture (PA) and Integrated Pest Management (IPM). Precision Agriculture serves as a catalyst for smart farming by employing technological solutions like Global Positioning Systems (GPS), drone surveillance, and soil and climate sensors [22]. These technologies empower farmers to make data-driven decisions, thereby enhancing crop yields while conserving essential resources like water and soil nutrients [23]. In a similar vein, Integrated Pest Management (IPM) contributes to the ecological balance of farming systems. This approach, grounded in biological and environmental understanding, integrates multiple pest control methods, ranging from biological controls to the judicious use of pesticides [24]. Studies reveal that IPM not only minimizes pesticide usage but also promotes ecological balance by preserving beneficial insects and natural predators [25].

Precision agriculture, a modern farming approach, relies on precise chemical use, including fertilizers, pesticides, and herbicides, tailored to factors like soil conditions and crop needs. [26] examined the effectiveness of various herbicides in managing post-emergence weeds in cotton fields. Their research provided insights into optimizing weed control strategies, enhancing crop productivity, and reducing weed-induced competition, addressing key challenges in contemporary agriculture. The fusion of PA and IPM has begun to receive scholarly attention due to its potential for synergistic benefits. The integration of real-time data collection from PA technologies with the multi-faceted pest control strategies of IPM can elevate the efficiency and sustainability of farming systems [27]. A study by [28] demonstrated that the targeted application of pesticides, guided by PA data, led to a significant reduction in chemical usage, aligning well with IPM principles. Technological Innovations stand at the forefront of this integration. Advances in Artificial Intelligence (AI) algorithms and machine learning models are enabling more accurate prediction of pest outbreaks, thereby allowing for timely and targeted interventions [29]. Internet of Things (IoT) devices provide the capability for continuous monitoring and data collection, a feature that enhances the dynamism and responsiveness of IPM strategies [18].

Various Case Studies corroborate the effectiveness of integrating PA and IPM. A research initiative in Iowa showed a 20% increase in corn yields when PA and IPM were synergistically applied [30,31]. Another case study in California's vineyards reported not just yield improvements but also a 30% reduction in water usage, a critical factor considering the growing concerns about water scarcity [32]. However, the integration of PA and IPM is not without its Challenges and Limitations. The high initial cost of technology adoption, particularly for small-scale farmers, remains a significant barrier [33]. Additionally, there exists a knowledge gap in fully understanding the long-term ecological impacts of combining PA and IPM, necessitating further research and field trials [34,35]. Innovative approaches within the integrated Precision Agriculture (PA) and Integrated Pest Management (IPM) framework include the utilization of heat sensor control for insect pests. This technology employs thermal imaging and heat sensors to identify localized temperature variations in fields, signaling potential pest activity. By integrating this data with other PA tools, farmers can precisely target and mitigate pest infestations, reducing reliance on chemical pesticides and promoting eco-friendly pest management practices [36,37].

Incorporating advances in Precision Agriculture, research has delved into its transformative impact on agronomic crops. Technologies such as Variable Rate Technology (VRT) have been pivotal in optimizing nutrient distribution across fields, thereby enhancing crop yields [38]. For instance, a seminal studied [39] demonstrated that the use of VRT for nitrogen fertilization in corn fields led to a 15% increase in yield while reducing nitrogen runoff, contributing to both economic gains and environmental sustainability. Similarly, soil electrical conductivity mapping, another PA tool, allows for the identification of different soil zones. This facilitates localized soil treatment, proving particularly effective for crops like wheat [40].

Another avenue where Precision Agriculture has shown promise is in the realm of irrigation management. Automated irrigation systems, governed by real-time soil moisture data, have been employed to conserve water resources while ensuring optimal crop growth [41]. A studied [42] found that the implementation of sensor-based irrigation systems in soybean fields led to a 20% reduction in water usage without compromising yield. This is particularly salient given the increasing global concerns about water scarcity. Moreover, PA has found applications in precision planting systems, offering plant-specific care that takes into account the individual needs of each plant. These systems have revolutionized the sowing of agronomic crops, with research showing that precision planting can improve the uniformity of plant stands and thereby enhance crop yields [43]. It's crucial to note that while the adoption of PA technologies in agronomic crops has shown promising results, challenges such as high initial investment costs and the need for farmer education still persist [44]. Therefore, while PA holds substantial promise for improving the productivity and sustainability of agronomic crops, targeted policy measures and educational programs are essential for its widespread adoption and efficacy.

3. INTEGRATION OF PRECISION AGRICULTURE AND IPM FOR CROP YIELD AND PROTECTION

3.1 Evolution of Crop Protection Methods

The evolution of crop protection methods offers a compelling narrative that underscores the pressing need for sustainable and efficient solutions in agriculture. Historically, traditional methods dominated the realm of crop protection, employing techniques such as crop rotation, manual removal of pests, and even rudimentary biological controls like the use of natural predators. While cost-effective and accessible, these approaches often lack the specificity and efficacy required to manage pest populations on a large scale [45,46]. Over time, the limitations of traditional methods led to the widespread adoption of chemical-based protections.

Chemical pesticides, including insecticides, herbicides, and fungicides, marked a significant advancement in crop protection when they were introduced. These substances offered highly effective, fast-acting solutions that could be applied on a large scale. However, the environmental toll of synthetic chemicals is substantial, affecting non-target species and leading to soil and water pollution [47]. Additionally, the overuse of chemical pesticides has contributed to the development of resistant pest populations, diminishing the long-term efficacy of these agents [48]. Biological controls emerged as an alternative, aiming to minimize the environmental impact of crop protection. This approach utilizes natural predators, parasites, and pathogens to control pest populations. Biological controls are lauded for their sustainability and low environmental impact. However, they often require intricate knowledge of local ecosystems and can be less effective or slower to act compared to chemical methods [49,50].

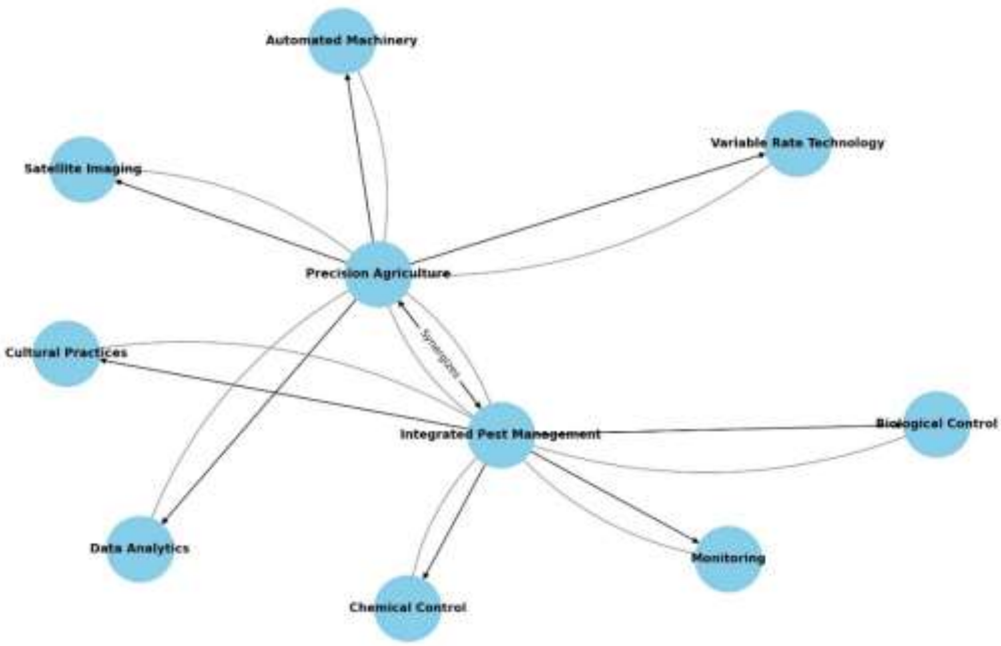

Fig. 1. Precision agriculture and integrated pest management

The above-mentioned methods, while beneficial in specific contexts, each possess inherent limitations in terms of efficacy, environmental impact, and scalability. These challenges set the stage for the integration of Precision Agriculture (PA) and Integrated Pest Management (IPM) as more advanced and holistic solutions. By leveraging cutting-edge technologies and a multifaceted approach to pest control, PA and IPM promise not only to enhance crop protection but also to do so in an environmentally sustainable and economically viable manner. Thus, the advent of PA and IPM can be seen as a natural progression in the evolution of crop protection methods, offering a balanced approach that capitalizes on the strengths and mitigates the weaknesses of traditional, chemical, and biological methods.

3.2 Precision Agriculture: An Overview

Precision Agriculture (PA) represents a paradigm shift in the realm of agriculture, embodying the integration of various technologies to manage and optimize field-level operations. At its core, PA is defined as the application of information technology and a range of hardware tools to enable high-resolution management of agricultural inputs. The scope of PA encompasses a range of technologies, including but not limited to, Global Positioning Systems (GPS), Variable Rate Technology (VRT), soil and climate sensors, and drone surveillance [51].

One of the most compelling advantages of PA is its potential for resource optimization. By using GPS and VRT, farmers can apply fertilizers, pesticides, and water with high spatial precision, thereby reducing waste and improving crop yields [39,52]. This not only makes the agricultural process more efficient but also mitigates its environmental footprint. For instance, the use of soil sensors can help manage irrigation more effectively, resulting in water conservation a critical benefit in regions facing water scarcity [53]. Moreover, PA's data-driven approach facilitates more informed decision-making. Technologies such as drone-based multispectral imaging can provide real-time data on crop health, allowing for timely interventions that can prevent crop loss [25]. Artificial Intelligence (AI) and machine learning algorithms further refine this data, offering predictive analytics that can forecast yields and potential pest outbreaks [29].

3.3 Integrated Pest Management: An Overview

Integrated Pest Management (IPM) stands as a pivotal advancement in the sphere of crop protection, offering a multi-pronged approach to mitigate the damage caused by various pests. By definition, IPM is a sustainable strategy that employs a combination of biological, physical, chemical, and cultural tactics to control pest populations below economically damaging levels [54]. Rather than solely relying on chemical pesticides, IPM integrates diverse methods, aiming for long-term pest control that minimizes environmental impact and maximizes economic returns.

Among the myriad strategies that constitute IPM are biological controls, which involve the introduction or encouragement of natural predators to manage pest populations. This not only reduces dependency on chemical methods but also promotes ecological balance within agricultural settings [55]. Physical controls such as trapping and barriers also form part of the IPM toolbox, providing localized solutions that can be particularly effective for certain pests [56]. Chemical controls are still employed but in a more targeted and judicious manner, reducing the risk of pesticide resistance and environmental degradation [57]. Furthermore, cultural practices like crop rotation and intercropping are integrated into IPM plans, leveraging plant diversity to disrupt pest life cycles [58].

3.4 Convergence of Precision Agriculture and Integrated Pest Management

The convergence of Precision Agriculture (PA) and Integrated Pest Management (IPM) represents a significant milestone in the field of sustainable agriculture, providing a harmonized approach to tackle the dual challenges of increasing yields and reducing environmental impact. PA's data-driven insights into soil conditions, microclimates, and plant health can serve to inform IPM strategies, allowing for more targeted and effective pest control measures [59]. For instance, drone technology equipped with multispectral cameras can provide real-time data on pest infestations, enabling timely interventions that align with IPM principles [12].

One noteworthy case study that exemplifies this integration comes from a research initiative in Iowa. The study showed that when PA and IPM were applied in tandem, corn yields increased by 20%, and pesticide use was reduced by 30% [30]. This clearly underscores the economic viability and environmental sustainability achievable through this synergistic approach. Technological advancements further catalyze this integration. The application of Artificial Intelligence (AI) algorithms can enhance the predictive accuracy of pest outbreaks, thereby allowing for preemptive control measures [29]. Similarly, the Internet of Things (IoT) enables continuous monitoring of field conditions, thereby making IPM strategies more dynamic and responsive [18].

3.5 Impact on Crop Protection and Yield

The confluence of PA and IPM technologies has the potential for far-reaching impacts on both crop protection and yield, with diverse quantitative and qualitative dimensions. Quantitatively, innovations such as Variable Rate Technology (VRT) and soil moisture sensors have proven instrumental in optimizing resource use. For example, a study conducted [11] indicated that VRT's application in nutrient management led to an impressive 18% yield increase in soybean fields. This jump in yield is not just an agricultural victory but also a socio-economic one, contributing to increased profitability for farmers and potentially lowering food prices for consumers. Qualitatively, the blend of PA and IPM offers a more sustainable approach to agriculture. Utilizing biological controls in tandem with targeted chemical interventions minimizes collateral environmental damage. A case in point is the worked [10], which reported a 25% reduction in water usage when sensor-based irrigation was integrated into an IPM strategy. This has broad implications for water conservation, an increasingly vital consideration given global climate change.

Moreover, the fusion of these advanced technologies also has broader socio-economic implications. Beyond the immediate increase in yields and the corresponding rise in farmer income, there's a ripple effect on employment in tech-related agribusiness and research sectors. Community-level benefits are also palpable, as more efficient and sustainable farming practices can lead to healthier local ecosystems and potentially lower food prices. Therefore, the merging of PA and IPM technologies appears to be more than just the sum of its parts; it signals a paradigm shift towards a more sustainable and economically viable future in agriculture [60]. The transition not only promises better crop yields but does so in an ecologically responsible manner, making it a cornerstone for the next generation of agricultural practices.

4. CHALLENGES AND FUTURE DIRECTIONS

Navigating the intricacies of Precision Agriculture (PA) and Integrated Pest Management (IPM) reveals a landscape of opportunities tempered by distinct challenges and future directions that demand scholarly attention. Among the most pressing technical challenges is the high initial cost of adopting PA technologies, particularly for small-scale farmers. Advanced sensors, drone technology, and data analytics platforms often require significant investments, which can serve as a barrier to widespread adoption [61]. Additionally, the complexity of these technologies necessitates specialized training and education, further complicating their adoption across diverse agricultural settings [62].

Regulatory and policy concerns also loom large. The use of drones, for example, is subject to airspace regulations that can vary from one jurisdiction to another. Similarly, the data collected through PA can raise privacy issues, necessitating clear guidelines on data ownership and usage [63]. There's also a need for policy frameworks that incentivize sustainable practices, such as subsidies for farmers who adopt IPM or tax benefits for those who invest in eco-friendly PA technologies.

Moreover, existing literature has largely treated PA and IPM as isolated domains, with limited research focusing on their synergistic integration [15]. This presents a research gap that future studies must address to unlock the full potential of merging these two fields. Investigating the most effective ways to integrate real-time data collection from PA with the multi-pronged strategies of IPM could yield significant advancements in sustainable agriculture. Future directions for research should aim to validate the benefits of integrating PA and IPM through extensive field trials and case studies. In addition, exploring the role of emerging technologies like Artificial Intelligence and the Internet of Things in enhancing the efficacy of PA and IPM could provide new avenues for innovation [29]. Researchers should also focus on developing scalable and cost-effective solutions that make the benefits of PA and IPM accessible to a broader range of farmers, including those in developing countries where the need for sustainable and efficient agricultural practices is often most acute [17].

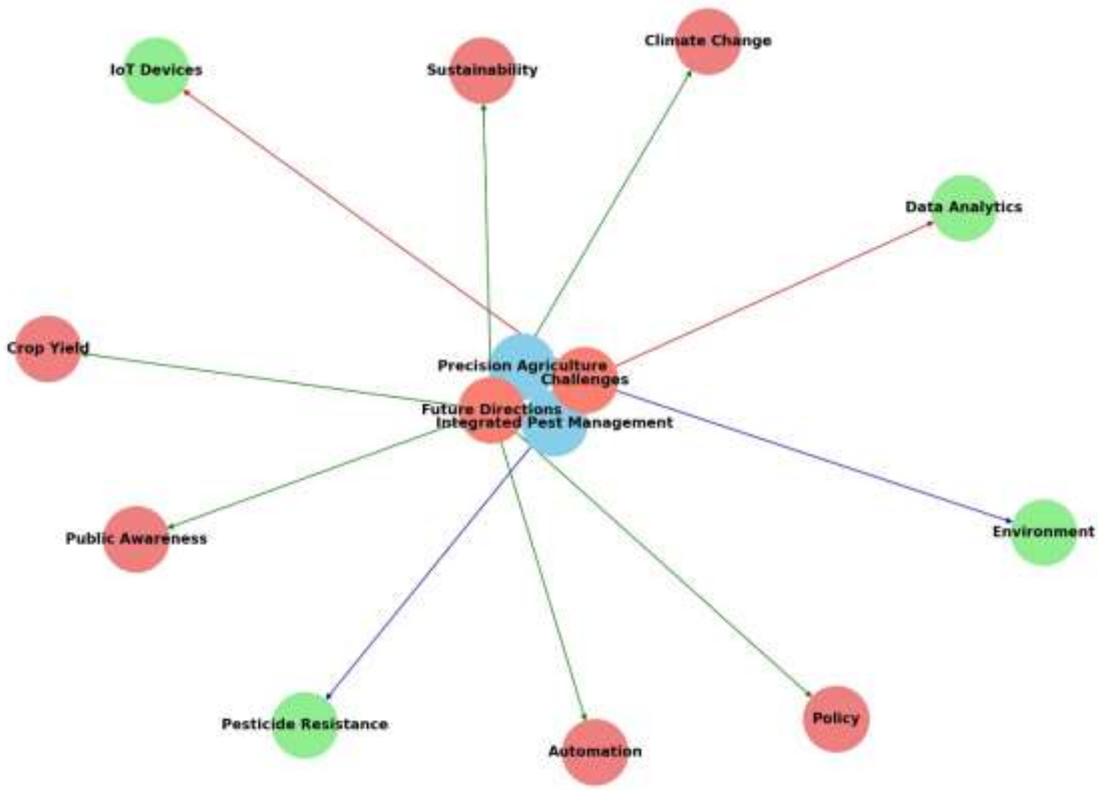

Fig. 2. Challenges and future directions diagram

Table 1. Comparison and synergy potential of Precision Agriculture (PA) and Integrated Pest Management (IPM)

Aspect	Precision Agriculture (PA)	Integrated Pest Management (IPM)	Potential for Synergy
Primary Goal	Optimization of field-level management with regard to crop farming	Effective, economical, and environmentally sound pest management	Combining PA technology with IPM practices can optimize both yield and pest control
Data Sources	Satellite images, soil sensors, drones	Pest traps, weather stations, field scouting	Integrated data analytics can refine both PA and IPM strategies
Technological Needs	Advanced machinery, data analytics software	Pesticides, biological control agents, minimal detection technology	Convergence of technologies can improve efficiency and sustainability
Environmental Impact	Aims to reduce waste and resource use	Focused on minimizing pesticide use and environmental harm	Synergistic approach can substantially lower environmental footprint
Cost Implications	Initial high cost for technology	Cost-effective in the long run but may require periodic investments	Combined approach can be cost-effective over time due to optimized resource use
Challenges	Data management, technology costs	Resistance development, correct identification of pests	Interdisciplinary expertise required for effective implementation

5. CONCLUSION

In closing, this review paper underscores the transformative potential of integrating Precision Agriculture (PA) and Integrated Pest Management (IPM) in advancing sustainable agricultural practices, particularly in the context of agronomic crops. The paper elucidates how PA technologies such as Variable Rate Technology, soil electrical conductivity mapping, and sensor-based irrigation systems offer avenues for optimizing resource use while enhancing crop yields. Similarly, the IPM approach, grounded in biological controls and judicious chemical use, contributes to ecological balance and minimizes environmental degradation. The confluence of these two domains promises a synergistic benefit, offering a more nuanced and effective strategy for crop protection and yield improvement. Significantly, the review identifies gaps in current research, particularly regarding the comprehensive integration of PA and IPM. While individual successes have been documented, the broader landscape of their combined impact remains underexplored. As global challenges like population growth and climate change put increasing pressure on agriculture, the integration of PA and IPM stands as a promising solution that warrants further empirical investigation. Future research should focus on case studies that explore the economic viability, long-term sustainability, and scalability of this integrated approach. By doing so, the agriculture sector can move closer to achieving a balance between productivity and sustainability, thereby meeting the demands of the 21st century in an ecologically responsible manner.

ACKNOWLEDGEMENTS

We are profoundly grateful to the authors and researchers whose work forms the foundation of this review paper. Our sincere thanks also go to our peers and reviewers for their constructive feedback and invaluable guidance.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Raimi MO, Ayibatonbira AA, Anu B, Odipe OE, Deinkuro NS. 'Digging Deeper' Evidence on water crisis and its solution in Nigeria for Bayelsa State: A study of current scenario. International Journal of Hydrology. 2019;3(4):244-257.
2. Searchinger T, Waite R, Hanson C, Ranganathan J, Dumas P, Matthews E,

Klirs C. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050. Final Report; 2019.
3. Kassem MA, Walters A, Midden K, Meksem K. Agricultural Sciences Conference-AMAS Conference III, December 13-16, 2016, Ouarzazate, Morocco; 2016.
4. Kassem MA, Walters A, Midden K, Meksem K. Proceedings of the Third International American Moroccan Agricultural Sciences Conference-AMAS Conference III, December 13-16, 2016, Ouarzazate, Morocco. Atlas Journal of Biology. 2017;313-354.
5. Nugroho AP, Sutiarso L, Okayasu T. Appropriate adaptation of precision agriculture technology in open field cultivation in tropics. IOP Conference Series: Earth and Environmental Science. 2019;355(1):012028.
6. Suprem A, Mahalik N, Kim K. A review on application of technology systems, standards and interfaces for agriculture and food sector. Computer Standards & Interfaces. 2013;35(4):355-364.
7. Paul K, Chatterjee SS, Pai P, Varshney A, Juikar S, Prasad V, Dasgupta S. Viable smart sensors and their application in data-driven agriculture. Computers and Electronics in Agriculture. 2022;198: 107096.
8. Baker BP, Green TA, Loker AJ. Biological control and integrated pest management in organic and conventional systems. Biological Control. 2020;140:104095.
9. Mouden S, Sarmiento KF, Klinkhamer PG, Leiss KA. Integrated pest management in western flower thrips: Past, present and future. Pest Management Science. 2017; 73(5):813-822.
10. El Wakeil N, Alkahtani S, Gaafar N. Is nanotechnology a promising field for insect pest control in IPM programs? In New Pesticides and Soil Sensors. Academic Press. 2017;273-309.
11. Zhang F, Cui Z, Fan M, Zhang W, Chen X, Jiang R. Integrated soil–crop system management: Reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. Journal of Environmental Quality. 2011; 40(4):1051-1057.
12. Rustia DJA, Chiu LY, Lu CY, Wu YF, Chen SK, Chung JY, Lin TT. Towards intelligent and integrated pest management through an AIoT-based monitoring system. Pest Management Science. 2022;78(10):4288-4302.
13. Chamara N, Islam MD, Bai GF, Shi Y, Ge Y. Ag-IoT for crop and environment monitoring: Past, present, and future. Agricultural Systems. 2022;203:103497.
14. Alwang J, Norton G, Larochelle C. Obstacles to widespread diffusion of IPM in developing countries: lessons from the field. Journal of Integrated Pest Management. 2019;10(1):10.
15. Johnson MA, Ruiz-Diaz CP, Manoukis NC, Verle Rodrigues JC. Coffee berry borer (*Hypothenemus hampei*), a global pest of coffee: Perspectives from historical and recent invasions, and future priorities. Insects. 2020;11(12):882.
16. Shahid AA, Rao QA, Bakhsh A, Husnain T. Entomopathogenic fungi as biological controllers: New insights into their virulence and pathogenicity. Archives of Biological Sciences. 2012;64(1):21-42.
17. Pretty J, Bharucha ZP. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. Insects. 2015;6(1):152-182.
18. Clay N. Seeking justice in Green Revolutions: Synergies and trade-offs between large-scale and smallholder agricultural intensification in Rwanda. Geoforum. 2018;97:352-362.
19. Misra NN, Dixit Y, Al-Mallahi A, Bhullar MS, Upadhyay R, Martynenko A. IoT, big data, and artificial intelligence in agriculture and food industry. IEEE Internet of things Journal. 2020;9(9):6305-6324.
20. De Clercq M, Vats A, Biel A. Agriculture 4.0: The future of farming technology. Proceedings of the World Government Summit, Dubai, UAE. 2018;11-13.
21. Gukurume S. Climate change, variability and sustainable agriculture in Zimbabwe's rural communities. Russian Journal of Agricultural and Socio-Economic Sciences. 2013;14(2):89-100.
22. Srivetbodee S, Igel B. Digital technology adoption in agriculture: Success factors, obstacles and impact on corporate social responsibility performance in Thailand's smart farming projects. Thammasat Review. 2021;24(2):149-170.
23. Liang C, Shah T. IoT in Agriculture: The future of precision monitoring and data-driven farming. Eigenpub Review of Science and Technology. 2023;7(1):85-104.

24. Barzman M, Bàrberi P, Birch ANE, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, et al. Eight principles of integrated pest management. Agronomy for Sustainable Development. 2015;35:1199-1215.
25. Torres JB, Bueno ADF. Conservation biological control using selective insecticides–a valuable tool for IPM. Biological Control. 2018;126:53-64.
26. Sajjad Z, Sabir MS, Siddique AA, Subhan M, Hashmi QA, Ali UZ, et al. Comparative evaluation of four herbicides for effective control of post-emergence weeds in cotton fields. Journal of Oasis Agriculture and Sustainable Development. 2023;5(4):19-26.
27. Paudel S, Sah LP, Pradhan K, Colavito LA, Upadhyay BP, Rajotte EG, et al. Development and dissemination of vegetable IPM practices and packages in Nepal. In Integrated Pest Management of Tropical Vegetable Crops. 2016;251-269.
28. Pertot I, Caffi T, Rossi V, Mugnai L, Hoffmann C, Grando MS, et al. A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. Crop Protection. 2017;97:70-84.
29. Balaska V, Adamidou Z, Vryzas Z, Gasteratos A. Sustainable Crop Protection via Robotics and Artificial Intelligence Solutions. Machines. 2023;11(8):774.
30. Korunić Z. Diatomaceous earths: Natural insecticides. Pesticidi i Fitomedicina. 2013;28(2):77-95.
31. Bottrell DG. Integrated pest management. Council on Environmental Quality; 1979.
32. Guerra K, Steenwerth KL. Improving vineyard water use efficiency and yield with variable rate irrigation in California. Agricultural Water Management. 2016; 164:1-8.
33. Grasswitz TR. Integrated pest management (IPM) for small-scale farms in developed economies: Challenges and opportunities. Insects. 2019;10(6):179.
34. Bommarco R, Öckinger E, Jonsson M, Ekroos J. Evaluating the ecological impacts of combining protected areas and integrated pest management. Trends in Ecology & Evolution. 2020;35(10):908-920.
35. Thompson DA, Lehmler HJ, Kolpin DW, Hladik ML, Vargo JD, Schilling KE, et al. A critical review on the potential impacts of neonicotinoid insecticide use: Current knowledge of environmental fate, toxicity, and implications for human health. Environmental Science: Processes & Impacts. 2020;22(6):1315-1346.
36. Aiello G, Giovino I, Vallone M, Catania P, Argento A. A decision support system based on multisensor data fusion for sustainable greenhouse management. Journal of Cleaner Production. 2018;172: 4057-4065.
37. Damos P, Escudero Colomar LA, Ioriatti C. Integrated fruit production and pest management in Europe: The apple case study and how far we are from the original concept? Insects. 2015;6(3):626-657.
38. Upadhyay K. Advancements in precision agriculture: A Review. Journal of Advanced Research in Agriculture Science and Technology. 2023;6(1):12-16.
39. Bongiovanni R, Lowenberg-DeBoer J. Precision agriculture and sustainability. Precision Agriculture. 2004;5:359-387.
40. Paccioretti P, Córdoba M, Balzarini M. FastMapping: Software to create field maps and identify management zones in precision agriculture. Computers and Electronics in Agriculture. 2020;175: 105556.
41. Liao R, Zhang S, Zhang X, Wang M, Wu H, Zhangzhong L. Development of smart irrigation systems based on real-time soil moisture data in a greenhouse: Proof of concept. Agricultural Water Management. 2021;245:106632.
42. Rajanna GA, Manna S, Singh A, Babu S, Singh VK, Dass A, et al. Biopolymeric superabsorbent hydrogels enhance crop and water productivity of soybean–wheat system in Indo-Gangetic plains of India. Scientific Reports. 2022;12(1):11955.
43. Hörbe TA, Amado TJ, Reimche GB, Schwalbert RA, Santi AL, Nienow C. Optimization of within-row plant spacing increases nutritional status and corn yield: A comparative study. Agronomy Journal. 2016;108(5):1962-1971.
44. Bucci G, Bentivoglio D, Finco A. Precision agriculture as a driver for sustainable farming systems: State of art in literature and research. Calitatea. 2018;19(S1):114-121.
45. Lucas P, Ratnadass A, Deguine JP. Moving from Integrated Pest Management to Agroecological Crop Protection (ACP). Agroecological Crop Protection; 2017.
46. Alphey L, Nimmo D, O'Connell S, Alphey N. Insect population suppression using

engineered insects. Transgenesis and the Management of Vector-Borne Disease. 2008;93-103.
47. Thatheyus AJ, Selvam AG. Synthetic pyrethroids: Toxicity and biodegradation. Applied Ecology and Environmental Sciences. 2013;1(3):33-36.
48. Blackie HM, MacKay JW, Allen WJ, Smith DHV, Barrett B, Whyte BI, et al. Innovative developments for long-term mammalian pest control. Pest Management Science. 2014;70(3):345-351.
49. Xiang L, Harindintwali JD, Wang F, Redmile-Gordon M, Chang SX, Fu Y, et al. Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. Environmental Science & Technology. 2022;56(23):16546-16566.
50. Downes DR. How intellectual property could be a tool to protect traditional knowledge. Columbia Journal of Environmental Law. 2000;25:253.
51. Bhakta I, Phadikar S, Majumder K. State-of-the-art technologies in precision agriculture: A systematic review. Journal of the Science of Food and Agriculture. 2019;99(11):4878-4888.
52. Finger R, Swinton SM, El Benni N, Walter A. Precision farming at the nexus of agricultural production and the environment. Annual Review of Resource Economics. 2019;11:313-335.
53. Evans RG, Sadler EJ. Methods and technologies to improve efficiency of water use. Water Resources Research. 2008; 44(7).
54. Bajwa WI, Kogan M. Compendium of IPM definitions (CID). What is IPM and how is it defined in the Worldwide Literature. 2002;15.
55. Deguine JP, Aubertot JN, Flor RJ, Lescourret F, Wyckhuys KA, Ratnadass A. Integrated pest management: Good intentions, hard realities. A review. Agronomy for Sustainable Development. 2021;41(3):38.
56. McEnnulty FR, Bax NJ, Schaffelke B, Campbell ML. A review of rapid response options for the control of ABWMAC listed introduced marine pest species and related taxa in Australian waters. Centre for Research on Introduced Marine Pests Technical Report. 2001;23:1-99.
57. Damalas CA. Safe food production with minimum and judicious use of pesticides. In Food Safety: Basic Concepts, Recent Issues, and Future Challenges. 2016;43-55.
58. Riemens M, Sønderskov M, Moonen AC, Storkey J, Kudsk P. An integrated weed management framework: A pan-European perspective. European Journal of Agronomy. 2022;133:126443.
59. Khang A, Rath KC, Panda S, Sree PK, Panda SK. Revolutionizing Agriculture: Exploring Advanced Technologies for Plant Protection in the Agriculture Sector. In Handbook of Research on AI-Equipped IoT Applications in High-Tech Agriculture. IGI Global. 2023;1-22.
60. Kesavan PC, Swaminathan M. Strategies and models for agricultural sustainability in developing Asian countries. Philosophical Transactions of the Royal Society B: Biological Sciences. 2008;363(1492):877-891.
61. White EL, Thomasson JA, Auvermann B, Kitchen NR, Pierson LS, Porter D, et al. Report from the conference, 'identifying obstacles to applying big data in agriculture'. Precision Agriculture. 2021; 22:306-315.
62. Genius M, Koundouri P, Nauges C, Tzouvelekas V. Information transmission in irrigation technology adoption and diffusion: Social learning, extension services, and spatial effects. American Journal of Agricultural Economics. 2014; 96(1):328-344.
63. Al Nuaimi E, Al Neyadi H, Mohamed N, Al-Jaroodi J. Applications of big data to smart cities. Journal of Internet Services and Applications. 2015;6(1):1-15.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/108114