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Virtual Reality in Agriculture: Applications and Challenges for Sustainable Farming

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Abstract
VR is becoming a revolution in the contemporary agriculture industry, as it provides immersive, interactive, and data-rich solutions that improve the decision-making process, training, and management of systems. This review will summarize the recent research in three areas of critical importance in crop management, pest management, and soil health by considering peer-reviewed literature, technology case reports and conceptual frameworks published between 2016 and 2025.The paper is methodologically thematic synthesis, after which the applications of VR are divided into categories in terms of functionality, seamless fusion with other technologies (e.g., drones, AI, IoT), as well as of interest to sustainable farming practices. The most important findings are that VR can be used to improve crop management by simulating fields and making precise interventions and visualization of data, pest control by virtual scouting, testing scenarios, and non-chemical integrated pest management (IPM), soil health education and monitoring based on 3D simulation and spatial analytics. All these applications prove that VR is a useful tool to enhance training, minimize operational risks, and make adaptive decisions. The review finds that VR has significant potential to be deployed in sustainable agriculture, but its larger-scale application is limited by the need to address issues that concern the cost of hardware, its usability, and the simulation fidelity and ethical concerns. Computer-assisted, VR combined with AI, IoT, and big data analytics will make it one of the main enablers of resilience-driven, precision-focused farming systems.

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1. Introduction

Virtual reality (VR) is a digital technology that enables users to perceive and interact with simulated environments—either real or imaginary—through immersive, multisensory systems Wohlgenannt, Simons, and Stieglitz (2020). VR devices such as head-mounted displays, motion-tracking controllers, gloves, and treadmills allow users to navigate complex scenarios and interact with virtual objects in a highly realistic and immersive manner Novacek and Jirina (2020); Kim, Rhiu, and Yun (2020). Although VR has gained widespread adoption across disciplines including entertainment, education, training, and healthcare due to its ability to create experiential and interactive learning environments Mäkinen, Haavisto, Havola, and Koivisto (2022); Pardini, Gabrielli, Dianti, Novara, Zucco, Mich, and Forti (2022); Yaqoob, Salah, Jayaraman, and Omar (2023), it is increasingly being recognized as a transformative technology within the agricultural sector.

Agriculture, a critical industry for global food security and economic stability, is facing growing challenges arising from population growth, climate change, soil degradation, pest outbreaks, and evolving consumer demands Gomez-Zavaglia, Mejuto, and Simal-Gandara (2020); Khan, Ray, Sargani, Ihtisham, Khayyam, and Ismail (2021); Jahan and Qale Nawi (2022). Addressing these multifaceted challenges requires innovative, data-driven, and sustainable approaches to production and resource management El Chami, Daccache, and El Moujabber (2020); Bennett, Baird, Baulch, Chaplin-Kramer, Fraser, Loring, and Lapen (2021). In this context, VR offers unique opportunities to enhance decision-making, training, planning, and visualization processes across the agricultural value chain de Oliveira and Corrêa (2020); Castiblanco Jimenez, Cepeda García, Violante, Marcolin, and Vezzetti (2020); Ashoka, Singh, Sunitha, Saikanth, Singh, Sreekumar, and Singh (2023).

Recent applications of VR in agriculture span a wide range of management domains. In crop production, VR-based systems enable the optimization of planting, irrigation, and harvesting strategies under varying environmental conditions Carruth, Hudson, Fox, and Deb (2020); Kumari, Raghuram, Venkatesh, and Shi (2022). For pest and disease management, VR supports early detection, scenario simulation, and virtual diagnostics, thereby facilitating integrated pest management practices Ponnusamy and Natarajan (2021); Garg, Sinha, and Singh (2022); Shoaib, Sadeghi-Niaraki, Ali, Hussain, and Khalid (2025). Similarly, VR technologies allow three-dimensional visualization of subsurface soil and water processes, supporting soil and water conservation planning and enabling more effective interventions by scientists and farmers Martínez-Graña, Goy, Zazo, and Silva (2016); Krzic, Strivelli, Holmes, Grand, Dyanatkar, Lavkulich, and Crowley (2013); Gerke, Vogel, Weber, Van der Meij, and Scholten (2022).

Beyond crop systems, VR is also gaining relevance in livestock management, agricultural education, and consumer interaction. Immersive environments contribute to improved animal welfare, enhanced learning experiences for rural communities, and the promotion of sustainable agricultural practices through experiential learning and virtual marketplaces Buller, Blokhuis, Lokhorst, Silberberg, and Veissier (2020); Klerkx (2021); Verhulst, Normand, Lombart, and Moreau (2017); Wells and Miller (2020).

This review paper provides a comprehensive overview of recent trends in the application of virtual reality technologies in agriculture, with a particular focus on crop production, pest management, and soil health. It critically examines current research and practical case studies to highlight the role of VR in improving visualization, decision-making, and experiential learning. Furthermore, the paper explores the strategic potential of VR for supporting sustainable farming systems, integrating precision agriculture technologies, facilitating climate change adaptation strategies, and enabling participatory planning processes. Finally, the review discusses the advantages and limitations of VR adoption in agriculture and outlines key recommendations to support the transition toward resilient, data-driven, and environmentally sustainable agricultural systems.

2. VR Applications in Crop Management

Crop management is defined as the process of planning, implementing, and evaluating agronomic practices and resource inputs that influence crop growth, development, and yield Meerman, Van de Ven, Van Keulen, and Breman (1996); Shah and Wu (2019). It encompasses a wide range of interrelated activities, including crop and variety selection, seedbed preparation, planting, irrigation management, nutrient application, pest and disease control, harvesting, and post-harvest operations Hussain, Ul-Allah, and Farooq (2023). The primary objective of crop management is to optimize the efficient use of inputs such as land, water, nutrients, labor, and energy while maximizing both the quantity and quality of crop yield Bolton (1981); Zhang, Cui, Fan, Zhang, Chen, and Jiang (2011); Riaz, Riaz, Arif, Yasmeen, Ashraf, Adil, and Fahad (2020).

Recent advances in digital agriculture have introduced immersive technologies—particularly virtual reality (VR)—that are reshaping traditional crop management approaches toward more productive, data-driven, and user-centered systems. VR offers unique capabilities for simulating crop growth dynamics, visualizing field conditions, training agricultural personnel, and supporting real-time, spatially informed decision-making processes. By integrating multisensory feedback and interactive environments, VR enhances situational awareness and strengthens the decision-making capacity of farmers, agronomists, and extension services Ponnusamy and Natarajan (2021); Kumari et al. (2022).

2.1 VR Headsets and Interactive Field Simulations

VR headsets and motion-tracked controllers enable users to explore three-dimensional worlds representing real or imagined crop fields. Such settings constitute simulated agronomic environments that allow users to virtually investigate plant development, identify symptoms of biotic or abiotic stress, and assess the effects of targeted interventions Bruno, Ceriani, Zhan, Caruso, and Del Mastro (2020); Tang, Dananjayan, Hou, Guo, Luo, and He (2021). An example of this approach is the use of simulated crop plots, which can be adjusted to experiment with different planting densities, irrigation schedules, or nutrient management programs, thereby providing a safe and cost-efficient experimental space.

VR has also been applied in educational programs to teach students and novice farmers how to detect crop diseases, adopt integrated pest management approaches, and perform sustainable field operations Stephens, Awasthi, Crowley, Boyle, and Walsh (2022). In such settings, VR enhances experiential learning by enabling lifelike scenarios that cannot be easily achieved due to seasonal constraints, logistical limitations, or potentially hazardous real-world conditions.

2.2 VR-Enabled Drones and Imaging Systems

The combination of VR and drone-based remote sensing continues to increase the applications of accurate crop control. Spatially rich data collected by drones equipped with high-resolution RGB, multispectral, and thermal cameras can be captured over crop fields and utilized to create immersive three-dimensional virtual environments for analysis Akbari, Almaadeed, Al-Maadeed, and Elharrouss (2021); Kumar and Rao (2021). These VR-based aerial surveys enable users to virtually fly within crop landscapes, observe spatial variations in plant health, and identify areas affected by drought stress, nutrient deficiencies, or pest outbreaks.

VR systems can also be used to generate detailed digital elevation models (DEMs), canopy height maps, and orthomosaics through photogrammetric techniques such as Structure-from-Motion (SfM) Eltner, Kaiser, Castillo, Rock, Neugirg, and Abellán (2016); Kalacska, Arroyo-Mora, and Lucanus (2021). These models are particularly valuable for terrain-based planning and for understanding microclimatic variability, which supports site-specific interventions such as variable-rate fertilizer application and precision irrigation.

2.3 VR Dashboards, Data Visualization, and Decision Support

VR analytics applications combine data from various field sensors, including soil sensors, weather stations, yield monitors, and unmanned aerial vehicles (UAVs), and display these data in an interactive VR format. Such dashboards assist users in visualizing crop-related information through spatial maps, real-time graphs, and dynamic models, thereby making complex datasets more accessible and interpretable Cadavid, Garzón, Pérez, López, Mendivelso, and Ramírez (2018); Gutiérrez, Htun, Schlenz, Kasimati, and Verbert (2019). For example, VR dashboards can simulate the effects of a nitrogen application plan over time or visualize crop responses to future heatwave scenarios under changing climate conditions.

Next-generation systems further integrate artificial intelligence and machine learning algorithms to extract patterns from large datasets, detect anomalies, forecast crop performance, and recommend best management practices Wolfert, Ge, Verdouw, and Bogaardt (2017); Iaksch, Fernandes, and Borsato (2021); Khan (2023). When embedded within VR environments, these decision-support tools enable intuitive scenario testing and collaborative decision-making among farmers, agronomists, and policy advisors.

2.4 Training, Experimentation, and Planning

In addition to the use of VR at the field level, it can be applied to train farm workers in equipment handling, the use of precision farming technologies, and the safe and proper application of chemicals. VR also facilitates participatory planning, allowing stakeholders to interact with future land-use plans, crop rotation strategies, and input allocation scenarios in an immersive and interactive manner Maio, Araújo, Marques, Santos, Ramalho, Almeida, and Santos (2024).

Notably, VR has the ability to recreate situations that are infrequent or unforeseen under real-life conditions, such as extreme weather events or pest outbreaks, and to provide valuable insights into risk preparedness and adaptive management strategies. The integration of virtual reality with drones, automation, and data analytics enables the development of futuristic smart farming systems that support precision agriculture, as illustrated in Figure 1. Such systems assist in real-time crop monitoring and management through advanced technologies, thereby supporting crop health and yield optimization.

Overall, VR technologies contribute to crop management in a comprehensive manner by enhancing visualization, experimentation, and data interpretation. When combined with remote sensing, the Internet of Things (IoT), and Artificial Intelligence (AI), VR offers a powerful solution for the development of efficient, sustainable, and adaptive precision agriculture systems. Nevertheless, the widespread adoption of these technologies remains contingent upon overcoming challenges related to system costs, end-user training, data interoperability, and field validation.

3. Virtual Reality Applications in Pest Control

Pest control forms one of the key elements of sustainable agriculture because pests such as insects, pathogens, weeds, and vertebrates present a significant threat to crop health and productivity. According to global estimates, pests can cause yield losses of up to 40% annually, negatively affecting food security and economic stability Sharma, Kooner, and Arora (2017); Agarwal and Verma (2020). Traditional pest control techniques, particularly the use of synthetic pesticides, have generated multiple challenges, including environmental degradation, impacts on non-target species, risks to human health, and the development of pest resistance Dhananjayan, Jayakumar, and Ravichandran (2020). These issues have intensified the need for alternative, innovative, and more sustainable pest management solutions.

One response to these challenges is the application of virtual reality (VR), an immersive and interactive three-dimensional simulation technology. Through the creation of realistic or hypothetical farming environments, VR can support education, surveillance, identification, and decision-making processes in pest control. The adoption of VR technologies aligns with the broader objectives of precision agriculture and integrated pest management (IPM), which aim to reduce chemical inputs while improving the accuracy and effectiveness of management decisions Chandler, Richards, Jenny, Dickson, Huang, Klippel, and Prober (2022); Mahenthiran, Sittampalam, Yogarajah, Jeyarajah, Chandrasiri, and Kugathasan (2021).

3.1 Benefits of VR in Pest Control

Virtual reality provides a set of new tools that are transforming pest control activities in agriculture by offering immersive, data-oriented, and sustainable alternatives to traditional approaches. These innovations include experiential training, remote diagnostics, predictive modelling, and related applications that contribute to the development of smarter and more resilient farming systems.

3.1.1 Enhanced Training and Education

VR-based training is one of the most effective innovations, offering immersive learning environments capable of recreating real-world pest outbreaks across various agricultural settings such as greenhouses, orchards, and open fields, while minimizing the risks and costs associated with real-world experimentation. Through interactive pest-identification games, students can differentiate between pest types and their life cycles (e.g., larval versus adult stages) and test control methods under virtual conditions Zhang and Qu (2020); Ennouri, Triki, and Kallel (2020).

Feedback mechanisms embedded within virtual reality (VR) systems provide real-time corrective and performance-related feedback, thereby enhancing knowledge retention and skill development Mahenthiran et al. (2021).

3.1.2 Innovation and Research Facilitation

VR environments can be used to conduct simulation-based experimentation, allowing researchers to model pest population dynamics under varying conditions such as climate variability, crop rotations, and control inputs Abdullah and Umer (2004); Wenjiang, Yue, Yingying, Huichun, Mingquan, Bei, and Linyi (2019). These virtual environments also provide a platform for testing smart pest control systems, including drones, robotics, and AI-based detection technologies, prior to their deployment in real field conditions Prabhakar, Thirupathi, and Mani (2022).

Visualization of pest dynamics across spatial and temporal scales enhances the understanding of infestation trends and supports predictive and adaptive approaches to pest management Rossi, Caffi, and Salinari (2012).

3.2 Technical Integration of VR in Pest Control

3.2.1 Smart Pest Management Systems

Although this review primarily focuses on Virtual Reality (VR), complementary modalities of Extended Reality (XR) are discussed where they support or overlap with VR applications in agricultural settings, namely Augmented Reality (AR) and Mixed Reality (MR). A representative example is smart pest management systems that integrate VR, AR, machine learning, and image recognition to enable real-time diagnostic tools. Such systems allow users to identify pest species, monitor infestation severity, and receive recommendations for organic treatments or targeted chemical applications Mahenthiran et al. (2021). The incorporation of these tools within VR environments enhances user immersion and improves diagnostic accuracy.

Similarly, AR technologies can overlay pest-related information onto real-world field views, enabling agricultural practitioners to visualize infestation zones, potential treatment areas, and environmental factors without leaving the physical environment. MR further extends these capabilities by allowing interaction with holographic pest models and hybrid interfaces, thereby supporting collaborative diagnostics and scenario testing within combined physical–digital environments. XR modalities are increasingly applied in agricultural education and decision-support systems, providing more context-aware solutions compared to fully immersive VR alone Naudé, Botha, Hugo, Jordaan, and Lombard (2024); Spyrou, Ariza-Sentís, and Vélez (2025). When integrated with artificial intelligence and sensor networks, these technologies become more accurate,

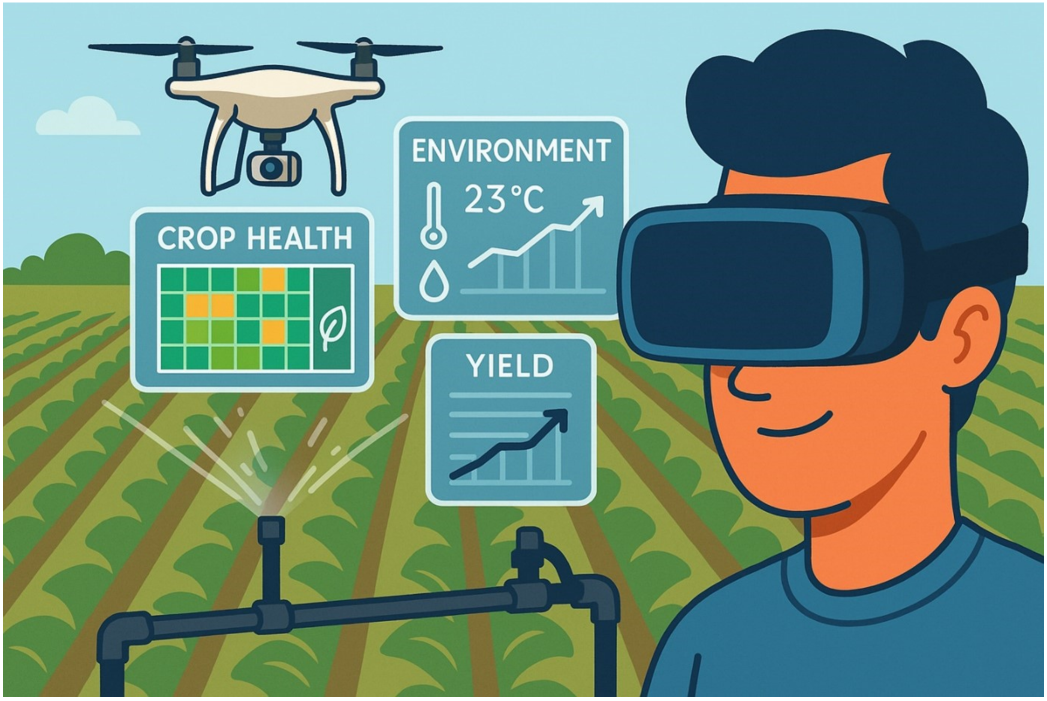

Figure 1. Illustration of a futuristic smart farming system integrating virtual reality (VR), drones, automation, and data analytics. A user wearing a VR headset represents the next-generation farmer managing precision agriculture using advanced technologies. The image depicts real-time crop monitoring with drone surveillance, automated irrigation, and data visualization panels for crop health, environmental conditions, and yield metrics.

accessible, and responsive in real time for pest management applications. To provide a structured overview of XR applications in agriculture, the key thematic areas are summarized in Table Table 1

3.2.2 Autonomous Drone Surveillance and VR Visualization

Autonomous drones equipped with multispectral and thermal cameras capture detailed field imagery in a systematic manner, which is subsequently processed into three-dimensional environments that can be visualized using virtual reality (VR). Agronomists and farmers can virtually fly over their fields, enabling early detection of pest outbreaks through heat signature analysis or vegetation stress indices Vanegas, Bratanov, Powell, Weiss, and Gonzalez (2018); Subramanian et al. (2021). These VR interfaces enhance spatial decision-making and facilitate site-specific treatments, ultimately reducing pesticide use and minimizing off-target effects.

3.2.3 Decision Support through VR Dashboards

VR-based decision support systems (DSS) integrate heterogeneous datasets, including meteorological information, soil health indicators, pest occurrence data, and crop phenology, into immersive dashboard environments Planas, Román, Sanz, and Rosell-Polo (2022). Users can explore simulated pest scenarios, evaluate alternative intervention strategies, and implement data-driven decisions in real time. Such interactive capabilities promote more informed planning and adaptive pest management, which are particularly critical under conditions of increasing climate variability.

3.3 Challenges and Limitations

Although VR applications show considerable potential, their use in pest control within agriculture faces several challenges that must be addressed to fully realize their contribution to sustainable agricultural systems.

- **Technical challenges** include the requirement for high-resolution hardware such as headsets and motion sensors, as well as powerful software platforms. These requirements can be prohibitively costly for smallholder farmers or under-resourced extension agencies. In addition, issues such as latency, software bugs, and device incompatibility may reduce the realism and credibility of VR-based simulations Li, Zheng, Yang, Li, Sun, and Yang (2021); Hahn, Fuchs, Fortna, Cobb, and Iqbal (2022).
- **User comfort and acceptance** also represent critical considerations, as some users experience cybersickness, nausea, or disorientation due to mismatches between visual stimuli and physical movement Chattha, Janjua, Anwar, Madni, Cheema, and Janjua (2020). Moreover, psychologically intensive simulated pest

Table 1. Summary of Extended Reality (XR) Technology Themes in Agricultural Research

XR Modality	Application Area	Key Functions
Virtual Reality (VR)	Pest management, training, simulation	Immersive diagnostics, scenario modeling, remote training Mahenthiran et al. (2021); Naudé et al. (2024)
Augmented Reality (AR)	Field scouting, decision support	Real-time overlays of pest data, environmental metrics, treatment guidance Subramanian, Pazhanivelan, Srinivasan, Santhi, and Sathiah (2021); Spyrou et al. (2025)
Mixed Reality (MR)	Education, collaborative planning	Holographic pest modeling, gesture-based interaction, hybrid learning environments Lorusso, Travellini, Giorgetti, Negrini, Reni, and Biffi (2020); Spyrou et al. (2025)
XR Integration	Smart pest management systems	Combined use of drones, thermal imaging, and immersive interfaces for precision agriculture Mahenthiran et al. (2021); Naudé et al. (2024)

scenarios may trigger stress or anxiety, particularly among vulnerable user groups Freeman, Reeve, Robinson, Ehlers, Clark, Spanlang, and Slater (2017).

- **Socio-ethical concerns** include the risk of user isolation, reduced community interaction, and cultural bias embedded within VR content Steuer (1992); Lorusso et al. (2020). Furthermore, the integration of VR systems with cloud-based decision-support platforms raises issues related to data privacy, liability, and regulatory oversight Brey (1999); Bailenson (2018).

Nevertheless, the increasing convergence of VR with artificial intelligence, the Internet of Things, and large-scale data analytics presents promising opportunities for precision-guided, adaptive, and sustainable pest management. Addressing these challenges through inclusive design principles, affordability, and ethical safeguards will be essential to ensure that VR technologies can play a meaningful role in the long-term sustainability of agricultural systems.

Figure Fig. 2 presents a conceptual representation of a VR-based pest control system in agriculture. It depicts a user wearing a VR headset and interacting with a digitally rendered field environment populated with realistic pest threats. The simulation illustrates real-time pest identification, decision-making interfaces, and scenario-testing modules, symbolizing the integration of sensory immersion with scientific modeling. This figure highlights the transformative potential of VR for future-oriented pest control through proactive, precise, and participatory approaches.

4. Virtual Reality Applications in Soil Health in Agricultural Systems

Soil health represents one of the central aspects of sustainable agriculture and refers to the biological, chemical, and physical properties that enable soil to function as a dynamic ecosystem supporting plant, animal, and human life Doran and Zeiss (2000); Lehmann, Bossio, Kögel-Knabner, and Rillig (2020). Healthy soils are essential for nutrient cycling, water retention, carbon sequestration, and disease suppression Bünemann, Bongiorno, Bai, Creamer, De Deyn, De Goede, and Brussaard (2018). However, intensive agricultural practices have resulted in severe soil erosion, climate change impacts, and excessive chemical use, which have collectively contributed to significant declines in agricultural productivity and environmental resilience Montanarella, Pennock, McKenzie, Badraoui, Chude, Baptista, and Vargas (2015); Lal (2012).

Monitoring, analyzing, and managing soil health require complex and spatially variable datasets. In this context, virtual reality (VR) technologies offer transformative potential. VR can support diverse stakeholders, including farmers, researchers, and educators, by enabling them to visualize soil conditions, evaluate management interventions, and enhance soil conservation practices through immersive and interactive environments.

4.1 Enhancing Soil Health Education and Training through VR

Traditional soil education often relies on textbooks, laboratory work, or field demonstrations, which may not fully convey the spatial complexity and dynamic processes of soil systems. Virtual reality (VR) technologies offer discipline-specific enhancements by enabling three-dimensional visualization of soil profiles, including layers, texture, structure, organic matter content, and biological activity Martínez-Graña et al. (2016). These immersive environments allow learners to explore soil processes such as infiltration, erosion, and respiration under varying land-use scenarios, thereby fostering a deeper understanding of soil functionality and degradation risks Tsai, Ho, Chang, Tsai, Yu, and Chiou (2019).

Unlike general agricultural training platforms, VR-based soil laboratories are designed to simulate soil-specific management interventions, such as tillage, cover cropping, or organic amendments, and to visualize their effects on soil structure and hydraulic behavior in real time Schlüter, Vogel, Ippisch, Bastian, Roth, Schelle, and Vanderborght (2012). For example, the *Virtual Soil Mechanics Laboratory* provides interactive modules focused on soil classification, compaction analysis, and parent material identification, supporting practical skill development in soil assessment del Cerro Santamaría (2000).

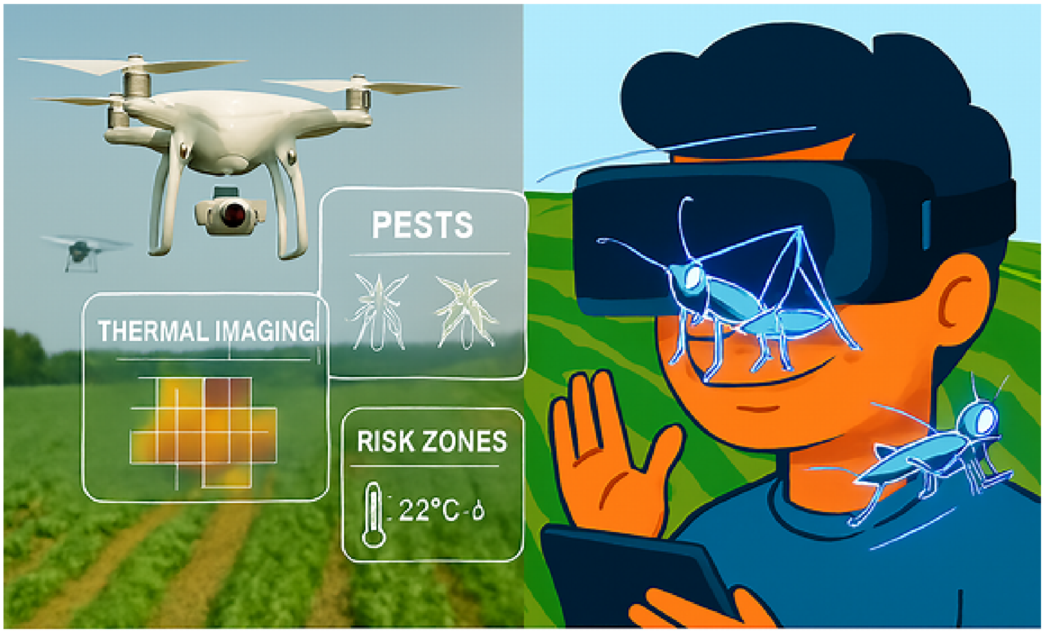

Figure 2. Application of Virtual Reality (VR) and Advanced Technologies in Modern Agricultural Pest Control. The image illustrates a farmer using a VR headset and handheld tablet to monitor pest activity in a crop field. Augmented reality (AR) overlays display identified pests (e.g., beetles, moths), risk zones, and environmental data in real-time. Aerial drones provide thermal imaging and surveillance to detect pest concentrations and crop stress, enhancing precision pest management. These Extended Reality (XR) tools, including AR and Mixed Reality (MR), complement VR by enabling multi-layered visualization, interactive diagnostics, and real-time decision support in both virtual and physical contexts.

Research in geoscience education further supports the use of VR for teaching soil formation, taxonomy, and spatial variability, demonstrating significant improvements in student comprehension and engagement Chenrai and Jitmahantakul (2019). These applications indicate that VR functions not only as a general training tool but also as a specialized pedagogical resource for advancing soil science education and promoting sustainable land management practices.

4.2 VR for Soil Monitoring and Visualization

Soil health exhibits substantial variability across both temporal and spatial scales, necessitating analytical tools capable of capturing dynamic patterns and long-term changes Ellur, Ankappa, Dharumarajan, Puttavenkategowda, Nanjundegowda, Sannegowda, and Dogançić (2024); Moemeni and Amirinejad (2025). When integrated with geospatial and sensor-based data—such as soil moisture probes, nutrient sensors, and remote sensing imagery—VR platforms enable the construction of immersive three-dimensional models representing soil landscapes Delarue, Cornu, Daroussin, Salvador-Blanes, Bourennane, Albéric, and King (2009); Gerke et al. (2022); Louzada, Bergier, Bolfe, and Barbedo (2025). These models allow users to explore subsurface variability at the field scale, identify zones affected by compaction or salinity, and assess the impacts of land management practices on soil function.

In contrast to pest-focused aerial surveillance systems, soil-specific VR applications emphasize below-ground dynamics and long-term ecological processes. For instance, hyper-temporal remote sensing approaches enhance the prediction of soil properties by capturing subtle spectral changes over time, thereby improving spatial diagnostics and supporting more effective soil conservation strategies Delarue et al. (2009). Similarly, three-dimensional representations of soil distribution facilitate a deeper understanding of spatial variability, which is essential for evaluating how interventions such as cover cropping or reduced tillage influence soil health across diverse landscapes Delarue et al. (2009); Gerke et al. (2022); Louzada et al. (2025).

These visualizations support the implementation of variable-rate technologies (VRT), which rely on data-driven prescription maps to optimize fertilizer application, irrigation, and tillage operations according to specific management zones Späti, Huber, and Finger (2021); He (2023). By integrating multiple soil data layers into immersive dashboards, VR enhances users' ability to interpret complex datasets and make informed decisions that promote sustainable land use and long-term soil resilience. As illustrated in Figure Fig. 3, virtual reality can be employed to provide immersive and interactive visualization of soil profiles and environmental data, thereby improving precision in agricultural monitoring.

4.3 Virtual Soil Simulations for Management Planning

Virtual reality (VR) technology enables users to simulate and compare soil management strategies under diverse environmental conditions, with a focus on below-ground processes and long-term ecological outcomes. Immersive VR experiences allow users to explore soil at a microbial scale and observe how specific interventions, such as tillage, cover cropping, or organic amendments, affect soil structure, porosity, and biological activity Whitman and Tredinnick (2025). Unlike pest-focused simulations, these models emphasize soil deformation, compaction, and erosion dynamics, offering insights into the mechanical and hydrological behavior of soils under different land-use scenarios Holz, Azimi, and Teichmann (2015).

VR-based farmland simulations further support management planning by visualizing the effects of rainfall variability, slope gradients, and crop rotations on soil health and productivity Akanle (2024). These tools enable users to evaluate the long-term impacts of conservation practices, such as biochar application or mulching, on soil organic matter dynamics and microbial resilience.

Augmented and virtual reality applications additionally enhance climate adaptation planning by allowing users to simulate changes in rainfall regimes and assess projected impacts on soil health and land use Metelitsa and Máñez Costa (2024). Within the context of climate-resilient agriculture, predictive modeling through VR helps farmers anticipate soil responses to drought, flooding, or heatwaves. Platforms integrating biophysical models with spatial data can simulate water infiltration, nutrient leaching, and erosion patterns under extreme weather scenarios. For example, VR-based decision-support tools have been developed to compare land management strategies, such as tree planting or reduced tillage, based on their effects on carbon sequestration, profitability, and soil erosion Lasseur, Laurenson, Ali, Loh, and Mackay (2023); Quarshie, Abdulai, Duncan, Kc, Roth, Sneyd, and Fraser (2023). By enabling interactive exploration of these outcomes, VR provides actionable insights into soil adaptation strategies for climate resilience.

These soil-specific simulations offer practical guidance for sustainable land management by bridging the gap between scientific modeling and farmer decision-making under conditions of environmental uncertainty.

4.4 Case Studies and Emerging Applications

Several initiatives have already examined the application of VR technologies in soil health research and practice. For instance, a virtual reality experience of soil at the microbial scale has been developed to enable the examination of real soil structures and microbial interactions using microcomputed tomography techniques Whitman and Tredinnick (2025). At the industry level, Valent BioSciences has introduced a global soil health initiative that allows users to visualize and study plant root development and microbial interactions at unprecedented resolution through three-dimensional root imaging technologies and VR devices Valent BioSciences (2019).

Interactive VR applications have also been employed in educational contexts to promote learning in soil and environmental sciences by providing immersive environments in which students can interact directly with soil properties and processes Tsai et al. (2019). More broadly, the use of VR and augmented reality (AR) technologies in agriculture supports precision farming and soil health monitoring by enabling farmers to visualize crop and soil data at multiple spatial scales, optimize management strategies, and enhance decision-making effectiveness Yin, Cao, Marelli, Zeng, Mason, and Cao (2021); Placidi, Morbidelli, Fortunati, Papini, Gobbi, and Scorzoni (2021). These developments highlight the growing role of VR in advancing soil health research, education, and agricultural practice.

The University of British Columbia (UBC) Virtual Soil Science Learning Resources Project developed VR-based modules to support instruction in soil formation, taxonomy, and physical properties, significantly improving undergraduate student comprehension. This initiative produced a series of open-access, web-based learning tools and interactive laboratory modules addressing key soil science topics, including soil classification and parent-material identification Krzic et al. (2013); Namba (2016). Student feedback indicated enhanced learning outcomes and deeper conceptual understanding, demonstrating the effectiveness of VR and blended-learning approaches in soil science education.

5. Conclusion

Virtual reality has become an innovative solution to contemporary farming, and it provides an opportunity to manage crops, control pests and improve soil health through the prism of immersion, interaction, and data volumes. VR improves the visualisation, training and precision interventions through virtual field simulations, drone integrated imaging systems and decision support dashboards throughout the agricultural value chain. VR can be used in crop management to experiment with agronomic methods, observe plant behavior and plan the allocation of resources due to a better situational awareness. In herbal control, the VR creates safer affordable methods by allowing virtual reconnaissance, early identification, and immersive training in line with the principles of integrated pest management (IPM). VR plays a role in sustaining land-use practices as

Figure 3. Virtual Reality Interface for Soil Monitoring and Visualization. A conceptual illustration depicting a user wearing a VR headset to interact with a 3D visualization of soil layers, plant growth data, and environmental metrics. The system integrates geolocation mapping, temperature readings, and real-time soil analytics to enhance agricultural decision-making and environmental monitoring.

well as modelling the effect of management in soil health, as it promotes the visualisation of complex soil processes and aids in education.

5.1 Implications

The implications of this review are given below:

- **Practical Implications:** VR technologies provide farmers and agronomists with new training, diagnostic, and decision-making tools that enhance operational efficiency and reduce input costs.
- **Managerial Implications:** VR platforms can be utilized by agricultural managers and extension services to improve workforce capacity, facilitate planning processes, and promote safer field operations.
- **Methodological Implications:** The integration of VR with artificial intelligence (AI), the Internet of Things (IoT), and remote sensing introduces innovative methodological frameworks for data visualization, scenario modeling, and adaptive management.
- **Policy Implications:** Policymakers are encouraged to support VR adoption by investing in infrastructure, promoting digital literacy, and establishing regulations that ensure equitable access and data privacy.

5.2 Limitations of the Study

Being a review paper, the study is constrained by the scope and size of the available published literature. It combines recent developments and applications of VR in agriculture but lacks empirical validation and field-based performance measurements. In addition, the rapid evolution of VR technologies implies that some of the tools and platforms discussed may become outdated or replaced by newer and more advanced systems.

The review primarily focuses on crop management, pest control, and soil health, while livestock, aquaculture, and post-harvest applications are not examined in detail. Moreover, although Augmented Reality (AR) and Mixed Reality (MR) are briefly mentioned to provide contextual background for extended reality (XR) integration, this study is explicitly limited to Virtual Reality (VR) applications and does not present a comprehensive evaluation of other XR modalities.

5.3 Directions for Further Studies

Future research should focus on:

- Empirical validation of VR tools in real-world agricultural settings, including cost–benefit analyses and user experience studies.
- Cross-sectoral integration of VR with other emerging technologies such as blockchain, Geographic Information Systems (GIS), and biofeedback systems to enhance traceability, spatial planning, and user immersion.
- Socioeconomic impact assessments to evaluate how

VR adoption affects smallholder farmers, rural communities, and gender equity in agricultural innovation.

- Development of open-access VR platforms tailored to local contexts, languages, and farming systems to promote inclusive technological diffusion.

By addressing these areas, future studies can strengthen the role of VR in building sustainable farming systems that are adaptive, participatory, and data-driven.

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