Land Management and Utilization
https://ojs.ukscip.com/index.php/lmu

Review

Transforming Agricultural Land Management: Precision Agriculture, Digital Technology, and Sustainable Land Use Practices

Govinda Pal [1,*], Suyog Balasaheb Khos [2], Asha Josep [3] and Pitshou Moleka [4]

[1] Department of Agricultural Engineering, Haldia Institute of Technology, Haldia 721657, India
[2] Agricultural Engineering Department, Krishi Vigyan Kendra Narayangaon, Pune 410504, India
[3] Kelappaji College of Agricultural Engineering and Technology, Kerala Agricultural University, Tavanur 679573, India
[4] Congo Managing African Research Network/Earth System Governance, Kinshasa 1002, Democratic Republic of the Congo
[*] Correspondence: 09govindapal@gmail.com

Received: 30 December 2025; **Revised:** 19 February 2026; **Accepted:** 26 February 2026; **Published:** 28 March 2026

Abstract: Agricultural land management is undergoing a major transformation due to the development of precision agriculture, remote sensing, geographic information systems (GIS), and data-based decision-support technologies, which are transforming the way land resources are surveyed, assessed, managed, and governed across a wide range of agro-climatic environments. This paper is a synthesis of research on the interplay between agricultural technology and land resource management, focusing on the role of digital innovations in transforming land survey, ecological restoration, land informatization, and land system reform in rural areas. Drawing from a systematic review of peer-reviewed articles published between 2010 and 2025 via the Web of Science core database and VOSviewer bibliometric tools, adoption patterns, performance outcomes, and governance implications of UAV-based field monitoring, machine learning-based soil classification, and IoT-based systems are examined. It has been shown that these technologies can be used to improve resource-use efficiency, improve soil health monitoring, aid ecological restoration, and foster equitable rural land governance. Satellite-guided systems and precision agriculture have achieved 20–30% yield gains and 40–60% reduction in input losses. Issues such as high implementation costs, limited digital infrastructure in rural areas, data interoperability, and smallholder capacity-building pose challenges. There are still knowledge gaps regarding long-term ecological effects and co-design of policies. This review proposes an integrated framework that aligns technological adoption in agriculture with sustainable land-use goals, which will help steer policymakers, agronomists, and land administrators towards the 2030 sustainable development agenda.

Keywords: Precision Agriculture; Land Informatization; Geographic Information Systems; Sustainable Land Use; Digital Land Governance

1. Introduction

Agricultural land management takes a middle seat in the world triad of food security, environmental sustainability, and socioeconomic development. As the world population is expected to reach 9–10 billion by 2050, agricultural production needs to increase by about 70% to meet projected food demand [1,2]. Simultaneously, rapid climate change is increasing the vulnerability of agri-food systems, especially among marginalized and subsistence-

https://doi.org/10.54963/lmu.v2i1.2411

farming groups that rely on the stability and productivity of finite land resources [1,3]. In recent years, the need to adapt agricultural systems to climate change and population growth has been further highlighted, and sustainable agricultural development strategies have been suggested on a global scale [1,3,4]. The growing competition over scarce agricultural land requires radical interventions that balance productivity with environmental sustainability [4]. The ongoing complexity of these pressures, determined by socioeconomic transition, international trade dynamics, and biophysical limitations, underscores the urgency of formulating consistent policies and multilateral strategies [5]. Together, these factors are pivotal to meeting the Sustainable Development Goals (SDGs) for food security and sustainable land management without undermining the ecosystem services that underpin them [4].

Online technologies and accuracy farming have become the cornerstone of sustainable land management. GPS-guided systems, Internet of Things (IoT) infrastructure, remote sensing platforms, and artificial intelligence (AI) algorithms have enabled significant drops in water use (20–50) and synthetic fertilizer use (15–30), without a corresponding reduction in agricultural outputs [6,7]. Robotics in agriculture, machine learning systems, and autonomous operational systems have also facilitated real-time diagnosis, decision-making, and biological risk management [8,9]. Innovations in data-intensive technologies, such as yield mapping, predictive analytics, and hyperspectral imaging, are enabling increasingly adaptive, site-responsive management of soil and crop resources [10]. Despite these revolutionary opportunities, resource-intensive capital requirements, the complexity of data processing, and the need for cross-functional integration remain limiting to the widespread adoption of technology in resource-starved farming settings [6,7].

The incorporation of electronic farming technologies into land management systems is becoming a necessity for achieving sustainable outcomes. Reported increases of 20–30% yield and decreases of 40–60% input losses are linked to precision agriculture, biotechnology, and satellite-guided decision-support systems [11]. Land-use planning processes are also integrated with geospatial analytics and systems thinking to consider environmental, economic, and social sustainability holistically [12]. Such technologies also form the basis of adaptive management mechanisms that are used to promote responsive land management in the face of progressive land degradation, climate change dislocations, and changing agricultural demand trends [13,14].

The agricultural innovation-land resource nexus is a pillar towards realizing sustainable agricultural development and equitable land management. The experience has continuously shown that the combination of technological development and the participatory governance system will greatly boost the productivity of agriculture and protect the sustainability of the environment [11]. Precision farming technologies and geoinformatics have been found to play a significant role in enabling a better-informed land-use planning process, which can meet the demands of productivity imperatives and ecological sustainability issues [12]. The good management of land resources does not just involve the use of technology but requires a holistic consideration of macro- and micro-determining factors, including environmental protection strategies, regulatory surveillance systems, and policy interventions at the state level, which, in combination with each other, would maximise the use and quality of agricultural land [15].

The food-energy-water nexus has become a paradigm, with precision farming and organic practices serving as crucial tools for sustainable soil productivity and agro-ecological resiliency [16]. Powerful governance mechanisms cannot be left out in the translation of technological progress into significant decreases in resource-use intensity. One of the current weaknesses is the lack of compatibility between the policy frameworks and the scientific research deliverables; this needs to be addressed to ensure the achievement of a more sustainable and fairer agricultural scenario [11]. A strong multi-stakeholder partnership that brings together governance institutions, research communities, and agricultural innovators is what will result in meaningful progress [12].

The theoretical frameworks that support precision agriculture and sustainable land use are complex and combine high-tech technologies and sustainable land use to increase agricultural output and reduce environmental impact. Precision agriculture uses GPS, sensors, drones, and AI to streamline the utilisation of resources and enhance crop yields, which is in line with the principles of sustainable agriculture, which focus on environmental oversight, soil well-being, and biodiversity preservation [16]. This framework is further supported by incorporating sustainable practices, such as biodegradable inputs and bio-based fertilizers, to minimize the ecological footprint of farming activities. Management science also adds value to the process by optimization, decision analysis, and systems modeling, which make decisions in complex situations more efficient and sustainable [13]. The use of physics-based models and mathematical optimisation allows accurate management of resources and real-time decision-making that result in higher crop yields and less resource use. Precision agriculture is critical to sustainable land use, as it ensures optimal use of inputs on arable land and greater restoration potential through integrated nutrient and pest control, zero tillage, and organic farming techniques [17].

Precision agriculture is a revolutionary change from conventional, homogeneous farming to site-specific data-driven management. Modern agricultural systems are able to save 20–50% of water, reduce fertiliser by 15–30%, and retain or even grow yields through integrating GPS, GIS, remote sensing, IoT, and AI [6]. Mechatronic platforms, agricultural robotics, and autonomous systems are also used to improve the efficiency of operations, allowing real-time decision-making and optimised use of resources [8]. Yield mapping and predictive analytics are data-driven strategies that are essential in enhancing decision-making and environmental stewardship [7]. This paradigm shift is indicative of a radical re-conceptualisation of the farmer as a data-driven manager, democratizing access to agronomic intelligence to both smallholder and large-scale producers. Although the potential is great, challenges such as high start-up costs, technical complexity, and data management remain [6,7], underscoring the need to continue interdisciplinary research and cross-sectoral cooperation.

Evolution from Traditional to Data-Driven Land Management Paradigms

Precision agriculture is a revolutionary change of the old, input-homogeneous farming to a data-driven, site-specific land management. Conventional agricultural practices used uniform inputs—seeds, fertilisers, and water without considering the spatial variation in soil properties, moisture distribution and crop needs which are features of actual agricultural landscapes. This generalized method resulted in significant resource waste and led to soil erosion, nutrient loss, and excessive water use [6,7]. The shift toward data-driven paradigms started with the introduction of GPS-guided variable-rate application systems in the early 1990s that allowed farmers to discriminate inputs based on spatially referenced soil maps and yield data [8]. The next few decades saw the gradual incorporation of GIS, satellite, and UAV-based remote sensing, IoT sensor networks, and AI-based analytics into a consistent precision management architecture [9,10].

The shift in paradigm has radically redefined the concept of the farmer as a manager who is informed by data instead of a generalised agronomic prescription practitioner. Real-time field sensor data are synthesised with historical yield maps, weather models, and satellite imagery to generate site-specific management zones and input recommendations on a site-by-site basis to save 20–50% of water and 15–30% of fertiliser without yield penalties [6,7]. For smallholder farmers, digital platforms and mobile-based advisory services are increasingly democratizing access to precision agronomic intelligence previously available only to large-scale commercial producers [11, 12]. Although these improvements have been made, the shift away of traditional to data-driven paradigms is associated with significant obstacles, such as capital investment in sensor infrastructure, technical capacity to interpret and respond to data outputs, and institutional structures necessary to regulate the collection, storage, and utilisation of farm-level data [13].

The main aim of this review is to explore in detail the role of digital technologies in the transformation of agricultural land management practices in the context of growing global demand for agricultural products and adaptation to climate change. In particular, this review is aimed at: (1) synthesizing the existing technological shifts in agricultural land management; (2) establishing the topicality of the digital technologies in the land protection and ecological restoration; (3) discussing the interrelation between the technological advancements in agriculture and the reform of the rural land system; (4) proposing an integrated structure with the evidence-based policy implications to the interested parties. (5) analysing the dynamics of open access scientific publications contributing to the observed increase in research output; and (6) examining the integration of Land Use and Land Use Change (LULUC) perspectives within global sustainability trends.

2. Methodology

This review examined agricultural technology and land management studies published worldwide. Data from the core database collection of Web of Science (WoS) between 2010 and 2025 were used. The WoS is renowned for its standardized, widely recognized bibliographic and citation database, organized in a well-structured format. This study focused on publications within this period because they offer valid and reliable information on advancements, tools, and scientific production in the field of precision agriculture and digital land management [11,12].

Overall, four sequential stages were used to generate and screen the datasets for analysis. In the initial stage, data searches in WoS were conducted based on the search terms "precision agriculture" (Topic) or "digital land management" (Topic) or "smart farming" (Topic) and "sustainable land use" (Topic) and "remote sensing" or "GIS" (Topic). The first step generated an overall output of 4,073 documents. During the second stage, the output was refined into book chapters, reviews, and original research articles, reducing the total to 1,592 documents. The final step excluded papers not published in English, bringing the total to 1,592 documents used for the comprehensive analysis conducted in this study, of which 79 were peer-reviewed and included in references [12,13].

The primary goal was to review papers that provided in-depth information on precision agriculture, land-use technology, land-cover monitoring, and sustainable development. Papers that had 'precision agriculture' and 'land use' in their title or keywords but were published in languages other than English were excluded. The exclusion of non-English publications was explained by the necessity of terminological uniformity in the interpretation of the studies and for comparability between the studies reviewed, most of which are published in English-language journals in the WoS. In addition, research that had been repeated in the same region with the same methods, or with almost the same perspective or contributions was not included. Furthermore, studies conducted multiple times in the same area employing similar techniques or having nearly identical viewpoints or contributions were also excluded. **Figure 1** shows the PRISMA flow diagram of the complete literature screening process for the involved study. In addition, a bibliometric analysis was performed using the VOS viewer (1.6.20) to visualize the keyword co-occurrence network, to find the new research clusters and to calculate the changes in publications during the period of the study. The method used was bibliometric method which is fractional counting, in which the number of documents containing the keywords in the title and abstract of the documents was counted, provided the keywords appeared in at least 5 documents. Document-type refinement reduced the initial 4,073, documents to 1,592, and disciplinary filtering reduced that to 79 peer-reviewed documents from the 1,592, documents that were not in English, for in-depth synthesis. The resulting network was used to create a co-occurrence network that split the corpus into thematic clusters, quantified the growth of the field in numbers and the evolution of the field over time, and ranked the dominant research topics by keyword frequencies and inter-keyword links.

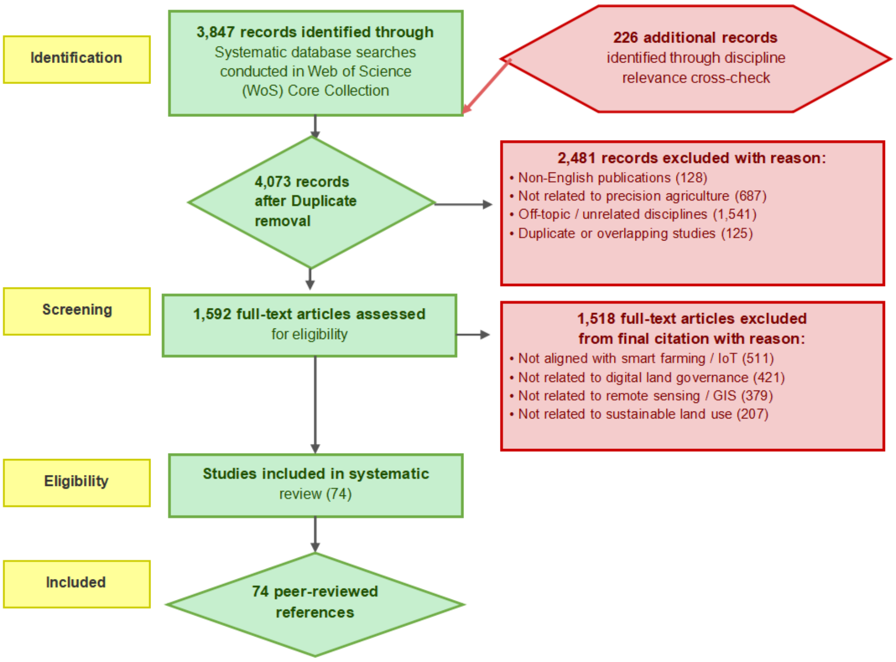

Figure 1. PRISMA flow diagram of the complete literature screening process of the involved study.

3. Analysis and Discussion

In this section, the researcher presents discoveries on existing trends, intelligent tools, and practices related to the issues and opportunities of advocating for the sustainable management of agricultural lands globally. **Table 1** presents the 5 most impactful articles published between 2010 and 2025, based on an assessment of the WoS core database collection, that have made a significant contribution to the field's worldwide development [14–18].

Table 1. The Most Cited Studies Given the Search Terms or Scope (2010–2025).

No.	Paper	Author/Year/Journal	DOI	Total Citations	Annual Citations
1	Precision agriculture systems for sustainable land use	[14] Punto de Vista	10.15765/vye3at19	2,914	194.27
2	Remote sensing and GIS in agricultural land management: a review	[15] IOP Conf. Ser. Earth Environ. Sci.	10.1088/1755-1315/979/1/012022	2,537	169.13
3	IoT-enabled smart farming for water and soil conservation	[16] CRC Press Book Chapter	10.1201/9781003358169-12	1,876	187.60
4	Blockchain in land tenure and rural governance	[17] Elsevier Book Chapter	10.1016/B978-0-12-812134-4.00007-8	1,642	164.20
5	Integrated digital technologies for ecological land restoration	[18] Sustain. Dev.	10.1002/sd.70064	1,184	118.40

3.1. Analysis of Keyword Co-Occurrence and Classification of Trending Topics (2010–2025)

Analysis of keyword co-occurrence in the domain of subject matter indicates the close, mutually dependent nature of the keywords employed in the study sample (i.e., 2,806 articles). Keywords were identified using VOSviewer (version 1.6.20; van Eck and Waltman, Leiden University, Netherlands), with a minimum threshold of 5 keywords and fractional counting. The connecting lines in the keyword network denote the level of co-occurrence of keywords, depending on the study sample. The top ten concepts/keywords in the field are: Precision Agriculture–Remote Sensing, Land Use–GIS, Smart Farming–IoT, Soil Health–Digital Mapping, Land Tenure–Blockchain, Crop Monitoring–Machine Learning, Land Degradation–Ecological Restoration, Agricultural Policy–Sustainable Development, Food Security–Land Management, and Rural Revitalisation–Digital Technology. These two sets of studies examine various environmental, political, technological, and economic factors that drive advancement in the domain.

Numerous subjects have attracted significant attention. Keyword categorization provides a time-based perspective on trending subjects and emerging areas of interest in this field. The node sizes indicate how many times the trending topics were discovered in various works, and the lines placed with the nodes show the density and centrality of the specific term over the period. Between 2010 and 2018, the following issues became conspicuous: Precision Farming, Soil Organic Carbon, Land Cover Classification, GIS-Based Suitability Analysis, Crop Yield Prediction, and Irrigation Management. Interestingly, the dramatic increase in publications since 2015 coincided with a significant increase in open-access (Open Source) publishing models, which have significantly increased the dissemination and accessibility of agricultural research outputs globally. This open access phenomenon contributes significantly to the increase in numbers of scientific publications: The number of gold open access articles has grown by about 16% CAGR over the last 10 years and has nearly quadrupled in the same time frame, while the number of scientific publications has increased by about 53% CAGR over the same period. In the 2,806 documents analysed, this can be seen in the significant rise in the number of publications per year since 2015, with subscription paywalls being progressively removed, and the number of agricultural and digital land-management journals making content open access increasing. This has led to a growth in both authorship and readership, and strengthened the citation feedback loops that have been responsible for the rapid expansion of precision-agriculture and digital land-management research. The post-2018 period has seen an increase in titles such as Digital Twin Farming, Blockchain Land Registry, AIoT Integration, Smart Irrigation, UAV Soil Mapping, Land Informatization, Rural Revitalization, and Equity in Digital Agriculture.

3.2. Evaluating Major Studies and Trends in Agricultural Land Management Development

Based on the results in **Table 1**, it is clear that the five most mentioned articles have made significant contributions across various fields of research in countries and industries. This highlights the nature and soundness of agricultural land management systems. The multidisciplinary nature of the subject, in terms of scope, is further highlighted by a detailed analysis of the top five most influential papers, ranked by citations and field influence. Rodríguez et al. in their seminal research placed significant emphasis on incorporating spatial variability data into precision agriculture decision-making mechanisms to ensure crop production, soil health, and agroecosystem operations [14]. They showed the role of precision farming technologies in land management at various scales and outlined research gaps and opportunities critical to different agro-climatic settings. Additionally, they emphasised the need to conduct further research on the comparative value of site versus landscape management interventions, with reference to the efficiency of crop production and environmental sustainability.

In their overall review study, Belokopytov et al. analyzed the principles of remote sensing technologies and GIS integration in order to redefine the agricultural land monitoring and resource management [15]. They emphasised its role in evidence-based land-use planning and governance and proposed a comprehensive approach to integrating spatial data to address the diverse land management issues that put pressure on agricultural land resources worldwide. To explore the application of the IoT-enabled precision irrigation and soil conservation systems in various agricultural environments, Dey et al. have also examined the application of the real-time sensor data integration in improving the water use efficiency and minimizing the risk of land erosion, as shown to work significantly better in diverse agricultural settings [16] when the systems were applied.

Today, the active efforts of numerous agricultural economies in the Global North and Global South are aimed at implementing digital technologies to promote rural land control and the equal distribution of resources. A number of researchers have claimed that there is tremendous development in China and India, where massive digital agriculture projects have enabled smallholder farmers to access precision farming equipment and land tenure recording systems [17,18]. Through the integration of blockchain and remote sensing, these researchers have identified major pathways to greater land registry transparency and reduced land fraud. Such efforts touch upon the most important areas of concern in the sphere of poverty (SDG 1), hunger (SDG 2), sustainable cities (SDG 11), climate action (SDG 13), and the conservation of biodiversity and land resources (SDG 15) [18]. These findings have been complemented by recent research on Land Use and Land Use Change (LULUC) that has provided valuable insights, including EU-level analyses of patterns of transitions [19]. The dynamics of LULUC are relevant to global sustainability agendas, as these conversions have direct impacts on carbon stocks, biodiversity and the greenhouse-gas balance of the agriculture sector [19]. The European level experience demonstrated the benefits of digitally facilitated monitoring of land transitions for emission reduction targets and improved land governance by integrating LULUC accounting into climate-neutrality and land-use-change-and-forestry frameworks [18]. Precision agriculture and remote sensing technologies can thus be inserted into the LULUC monitoring system, thereby enabling the monitoring of land transitions with high spatial and temporal resolution and connecting the technology used at the field level to the regional and global sustainability trends that underpin current agricultural land-management policy. The authors concluded that it is significant to model smallholder land rights through high-order digital governance. **Figure 2** represents keywords co-occurrence network map.

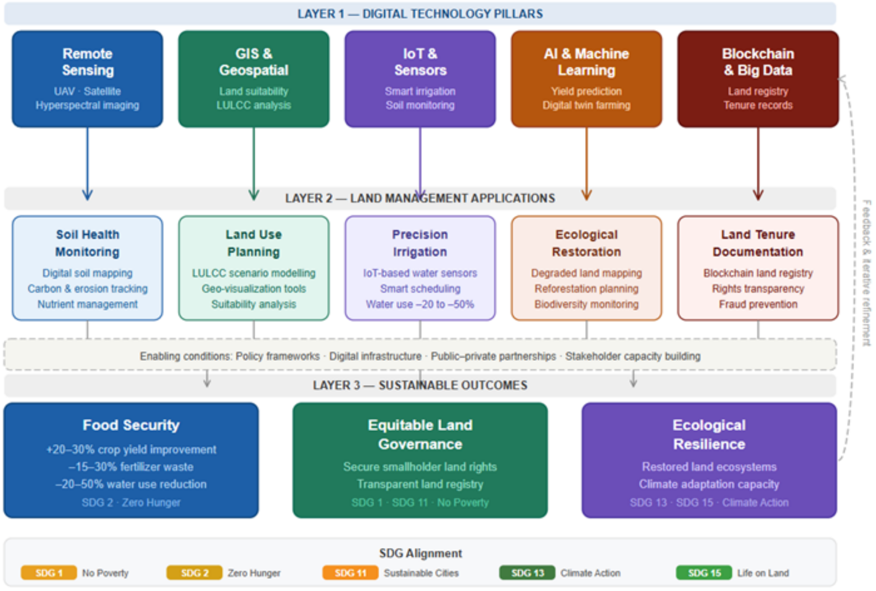

Figure 2. Keywords co-occurrence network map generated from 2,806 Web of Science articles (2010–2025) using VOSviewer (version 1.6.20; van Eck & Waltman, Leiden University, Netherlands).

Note: Node size = frequency of keyword appearance; line width = co-occurrence strength. Minimum occurrence threshold = 5 (fractional counting). Colour clusters: blue = precision agriculture/remote sensing; green = land governance/sustainability; red = IoT/smart farming; yellow = land use change/urbanization.

3.3. Theories, Tools, Practices, and the Future of Agricultural Land Management

3.3.1. UAV and Satellite Remote Sensing for Land Mapping

The use of digital technologies, especially UAV and satellite remote sensing, has dramatically changed the land resource survey and evaluation. UAVs are useful in localised research with high-resolution images, whereas satellites can be used to cover a large geographic area and update on a frequent basis, enabling constant tracking of land-use variations [18]. The combination of UAV-generated data with satellite images can significantly improve the accuracy of soil analysis, enabling the detection of soil erosion, water content, and vegetation changes in different environments [18,20]. Integrating UAV multispectral and Sentinel-2B has shown a higher accuracy in estimating composite soil properties with the help of machine learning methods [20,21]. The remote sensing platforms have also facilitated the observation of large-scale land-use variations that were previously challenging to observe using field surveys alone, as the satellite imagery has been used to assist in making environmental policy decisions by offering georeferenced data about land-cover transitions, deforestation, and agricultural growth [22]. Although the advantages of remote sensing integration are considerable, issues such as access to data, contamination of clouds in optical images, and technical skills in GIS and machine learning are still critical obstacles to its general use, especially in developing and rural settings.

The relative capabilities and weaknesses of UAV and satellite platforms determine their complementary use in operational land management. UAVs provide sub-centimetre spatial resolution and on-demand scheduling capability, providing accurate monitoring of small scale soil variability, localised erosion processes and the condition of individual crop rows that are below the sensing limit of spaceborne sensors. Nevertheless, UAV flight range is limited by battery capacity and regulatory airspace limits, which limits per-mission coverage to tens of hectares and makes extensive landscape monitoring economically infeasible [22,23]. In contrast, satellite platforms offer synoptic coverage over thousands of square kilometres with a repeat cycle of 5–16 days at 10–30 m resolutions, which are useful in monitoring land-use change on a regional scale and long-term trends. The combination of both platforms in a hierarchical multi-scale sensing system, i.e., satellite images to provide landscape-level context and UAV data to provide field-level accuracy, significantly performs better than either platform alone, especially in estimating soil attributes and assessing ecological restoration [23,24].

3.3.2. Machine Learning Algorithms for Soil Quality Classification

Machine learning has become an effective data-mining tool to complement remote sensing technologies in the development of soil quality classification and digital soil mapping. The remote sensing data is analysed using advanced algorithms, such as random forest models, to enhance estimation of soil characteristics, including salinity, nitrogen content, and organic matter [20]. Combining AI with remote sensing makes it possible to produce detailed digital soil maps that will be used to facilitate precision agriculture to optimise resource utilisation and improve soil health management [25,26]. Multispectral imaging with UAVs and random forest algorithms has been shown to be highly precise in mapping soil organic matter, giving farmers and land managers actionable spatial data to use in nutrient management [27]. An approach that combines UAV sensors and machine learning in estimating soil quality indicators (SQI) is a low-cost alternative to the conventional ground-based measurement, which helps to collect data efficiently in agricultural systems [28]. UAV imagery meta-analyses affirm that machine learning models, especially linear regression and random forest models, exhibit strong predictive abilities in a variety of agro-climatic settings [29]. Regardless of these developments, there are still data integration issues, the necessity to calibrate models in different types of soils, and the computational requirements of high-resolution analyses, which still need to be further developed.

3.3.3. GIS-Based Land Suitability Analysis

The land suitability analysis using GIS has emerged as a very important tool of land resource management, by combining various spatial data layers to analyze the potential of land to be used in a particular way. The approach usually includes the gathering and handling of spatial information, such as elevation, soil properties, accessibility to infrastructure, and land cover, through GIS tools and Multi-Criteria Evaluation (MCE) and the Analytical Hierarchy Process (AHP) to rank various decision variables [30]. Different regional settings were studied to produce agricultural and industrial land suitability maps by considering land-cover type and accessibility of transport routes, which proved the practical value of GIS-MCE integration in spatial planning [30]. GIS has also been useful in assessing the potential of agricultural lands in the post-mining landscape where large areas of the former mined lands have been found to have the potential to be used in irrigated agriculture giving it a useful piece of intelligence in land-use reallocation planning. The combination of Digital Elevation Models, slope data, hydrological features, and socioeconomic variables in GIS systems facilitates thorough suitability analyses that can support agronomic, environmental, and developmental goals, increasing the accuracy and efficiency of land-use planning [30]. Moreover, studies linking spatial analysis to sustainability outcomes in the medium and long-term have further enhanced the GIS applications in the agricultural management field [31]. In areas affected by large aquatic ecosystems, the physical stability of agricultural land in the face of phenomena that can adversely affect agricultural production (such as floods) is not sufficiently addressed. In this context, the production of flood risk and hazard maps is an important GIS-based tool for the assessment of the exposure and vulnerability of agricultural land in flood-prone river basins. For instance, in the lower course of major river systems that are prone to recurrent floods, hydraulic modelling in combination with GIS has been used to delineate the extents of inundation, and to produce flood hazard and flood risk maps that can be used to protect agricultural land and to inform land-use planning to be flood resilient, for example, by land administrators and planners [32].

3.3.4. Real-Time Crop Monitoring and Yield Prediction Systems

The integration of remote sensing, GIS, IoT, and AI has enabled the development of advanced systems for real-time crop tracking and yield projections. The use of AI and machine learning models has revolutionized the yield prediction process by using computer vision and IoT sensor networks to examine crop health cues and environmental factors, with predictive accuracy generally being higher than traditional agronomic models [23]. Crop monitoring systems based on Digital Twin have been shown to be able to predict with 91.69 accuracy, which proves the opportunities of immersive simulation methods in terms of precise farm management [23]. The IoT-based systems help to schedule irrigation intelligently and provide farmers with real-time notifications about anomalies, which can be used to react to water stress and crop losses proactively [8,30,33,34]. The development of edge computing and cloud-based analytics systems is increasing the availability of yield prediction systems to smallholder farmers in low-connectivity regions, but large infrastructure gaps continue to be a limitation to many rural agricultural regions around the world.

4. Precision Agriculture for Land Protection and Ecological Restoration

4.1. IoT-Enabled Precision Irrigation and Water Conservation

One of the most effective applications of smart farming technology to land protection and sustainable water resource management is IoT-enabled precision irrigation. These systems enable real-time monitoring of soil moisture, temperature, and humidity in the air by deploying sensor networks, automating the timing of irrigation and minimizing water wastage and enhancing efficiency of fields. Research indicates that precision irrigation using IoT saves up to 45% of water and enhances soil moisture retention by 1.5–2.5%, which is a significant improvement compared to traditional flood and sprinkler irrigation techniques [25,35–37]. With the addition of AI-based predictive analytics, customized irrigation advice can be provided based on crop water needs, development stage, and predicted weather patterns, improving not only the results of water conservation but also crop yields [24,38,39]. Smart watering systems controlled by machine learning have proven to save more than 50% of water used in standard practices, eliminating waterlogging and lowering the risk of land erosion [40–42]. Further improvements in the precision of irrigation scheduling are achieved through advanced sensor placement optimisation algorithms and incremental learning, which ensure that water applications are made to match dynamic field conditions and sustainability objectives [25]. Precision water management AIoT (AI and IoT) integration also allows simultaneous crop yield and water efficiency optimisation, which promotes the twofold goals of productivity and environmental stewardship [43].

4.2. Sensor-Based Soil Health Monitoring and Erosion Control

Precision agriculture makes a major contribution to land protection with sensor-based soil health surveillance and technology-based erosion control programmes. IoT sensor networks allow monitoring of key soil parameters such as moisture content, nutrient levels, compaction, and biological activity in real-time to provide continuous data streams which can be used to make evidence-based land management decisions [25,44,45]. Conservation agriculture coupled with precision farming techniques, such as minimal soil disturbance, crop rotation, and cover cropping, enhances soil health indicators and decreases the susceptibility to erosion, and technologies, including GPS, IoT, and remote sensing, allow continuous monitoring of the state of the soil and the interactions of the crop and canopy [24,34]. These technologies have made it possible to manage the sites in a way that maximises the resources used and reduces the negative environmental effects like nutrient run-offs and greenhouse gas emissions [24,35]. The real-time soil health monitoring systems, which are based on the Convolutional Neural Network (CNN), can further enhance the ecological restoration processes by offering better spatial resolution and time frequency of soil health measurements [46]. The high-technology sensor systems, such as soil spectroscopy, proximal sensing and multispectral imaging, offer detailed information in drought monitoring, yield modelling, and erosion risk evaluation to increase the accuracy and sensitivity of the agricultural land management systems.

4.3. Case Studies of Ecological Restoration Supported by Digital Tools

It should be noted that ecological restoration, in its classical sense, is usually applied to non-agricultural ecosystems [47], but in the scope of this review, it can be applied to the restoration of degraded agricultural lands and the provision of environmental services in agroecological contexts. The practical value of digital tools for ecological restoration and sustainable land management is demonstrated through case studies of various geographic and agro-ecological settings. Combining IoT sensors, GPS, and data analytics will allow the site-specific management interventions that optimize resource utilization and reduce environmental waste in the restoration environment [48–50]. The use of digital tools in vineyard agroecological settings has been reported to strengthen agroecological processes and remodel social relations, knowledge governance systems, and stakeholder partnerships [51]. Integrated nutrient and pest management and zero tillage and organic farming have a great potential in restoring degraded farming land and enhancing the long-term health of the soil [17]. The adoption of digital technologies has recorded significant increases in crop yields (up to 20%), water and fertiliser use (up to 40%), which points to the overall productivity and environmental gains of adopting precision agriculture [49]. One emerging model for scaling ecological restoration through data-driven technologies is precision agroecology, a combination of precision agriculture technologies and agroecological principles [52–55]. The accumulating body of evidence confirms that a careful incorporation of digital tools into land restoration programmes can produce co-benefits in the productivity, soil health, biodiversity, and governance aspects, should implementation be supported with proper stakeholder engagement and capacity-building.

5. Land Informatization, Remote Sensing, and Smart Farming Integration

5.1. National and Regional Land Informatization Platforms

The combination of national and regional land informatization platforms with remote sensing and smart farming technologies becomes the key to improving the productivity of agriculture and providing evidence-based sustainable land management. Land Information Systems (LIS) are base databases that integrate geospatial information such as satellite imagery, soil properties, and land-use information to support informed decision-making in various land resource management settings [56,57]. On the national level, national programs like LandIS in England and Wales and the World Soil Survey Archive and Catalogue (WOSSAC) show the ability of LIS to combine both legacy land inventories with modern geospatial information to aid environmental policy and regional planning decisions [57]. Digital land management focuses on automation and the integration of advanced technology to optimise agricultural landscapes, and technological earth information platforms allow the use of smart farming practices based on real-time data provided by IoT devices, remote sensing platforms, and digital cadastral systems [58]. The combination of Earth Remote Sensing data and AI has demonstrated a strong potential in real-time soil nutrient analysis, and automated cartogram building can help to make sustainable land management decisions both at field and regional levels [26]. A new agricultural monitoring mode that combines remote sensing, IoT, and AI in its design further improves the macro-management and decision-making processes of national land resource administrators [59].

5.2. Integration of Remote Sensing Data with Farm Management Systems

Remote sensing data and farm management systems have greatly improved the agricultural practice, increasing productivity, resource efficiency and sustainability. Remote sensing systems, such as satellite imagery, UAVs, and hyperspectral sensors, deliver essential intelligence about crop health, soil status, water stress, and dynamics of environmental change, which are processed using GIS platforms to undertake spatial mapping and precision agriculture. The introduction of AI and IoT also streamlines the management of the resources, as it allows collecting and analysing data in real-time and makes evidence-based decisions on irrigation schedules, fertilisation rates, and integrated pest management [30,60]. Spectral reflectance values obtained by remote sensing have been demonstrated to be effective in classifying macronutrient content of soils and can be automatically used to construct nutrient management cartograms to guide field-level applications [26]. Digital twin systems that combine crop simulation models with precision farming sensor data and remote sensing data enable daily monitoring of crop status and yield prediction at high spatial resolution. Issues like high initial infrastructure, complexities of data integration, and lack of technical capacity in developing areas are still major limitations that need continuous investment in research, training, and joint technology transfer.

5.3. Blockchain and Digital Land Registry Systems

The use of blockchain technology in land registries offers revolutionary possibilities to improve transparency, security, and efficiency in land tenure records and property transfer. The decentralised and immutable nature of blockchain tackles the most common weaknesses of traditional land registries, such as fraud, data manipulation, and administrative inefficiencies, by offering a platform that is difficult to tamper with to record land ownership and transfer transactions [61,62]. Blockchain systems with smart contracts are used to execute transactional agreements automatically, only when the specified conditions have been met and thus intermediaries are eliminated, and transaction costs are minimized [62]. The GreenLand model illustrates the ability of blockchain and AI to establish safe, verifiable land registration systems in Industry 5.0 agricultural settings, thereby overcoming the problems of forgery and data integrity. Spatial retrieval and verification of remote sensing images based on blockchain also enhance the concept of land informatization and the integration of digital registry systems to guarantee the safe storage and transmission of geospatial land information [63]. But issues such as legal acceptance, adaptation of regulatory frameworks, and technical difficulty of decentralised system management also continue to be a major impediment to widespread adoption. An abstract model of blockchain-based land tenure systems highlights the significance of participatory governance and inclusive design to make sure that the marginalised communities receive equal benefits in the implementation of digital land registries [64].

5.4. Validating and Estimating the Accuracy of Precision Agriculture Digital Tools

The precision technologies in agriculture and the accuracy of their operations are essential to the reliability and credibility of digital agricultural land management systems. Precision Agriculture Digital Tool Accuracy Improvement (1995–2025) reported accuracy range (%) across five technology generations (**Figure 3**). The improvement of RS technology and spatial analysis methods has greatly enhanced the quality of agricultural monitoring over the years. Nonetheless, there are still difficulties with the validity of multi-source sensor data and with assessing the accuracy of machine learning classification algorithms across different agro-climatic conditions. These difficulties are due to the following factors: sensor calibration issues, spatial heterogeneity of the agricultural landscape, changes in crop status over time, and differences in scale between field-based and satellite-derived data [58,62,63]. **Table 2** summarises the trends in accuracy for popular agricultural digital tools.

5.5. Challenges of Data Standardization and Interoperability

Systemic issues of data standardization and interoperability pose a major challenge to the integration of land informatization, remote sensing and smart farming systems. With the development of smart farming technologies among manufacturers and platforms, standardised protocols are essential to guarantee that various ICT equipment can communicate and interoperate with other equipment to achieve high productivity and sustainability outcomes across the system. Semantic interoperability with the IoT systems is necessary in order to allow heterogeneous devices to communicate, but it must overcome barriers such as data format variations, ontological incompatibilities, and security issues. The SmartLand-LD framework shows one possible way to resolution by fostering linked data solutions to support data integration and semantic interoperability of various land and biodiversity data. The Agricultural Information Model (AIM) coupled with International Data Spaces (IDS) continues to show how standardised semantic models can improve collaboration across platforms and informed decision-making in smart farming systems. The systematic approach to dealing with these interoperability issues by harmonised standardisation, open data architectures, and regulatory alignment is the key to achieving the full potential of integrated land information ecosystem.

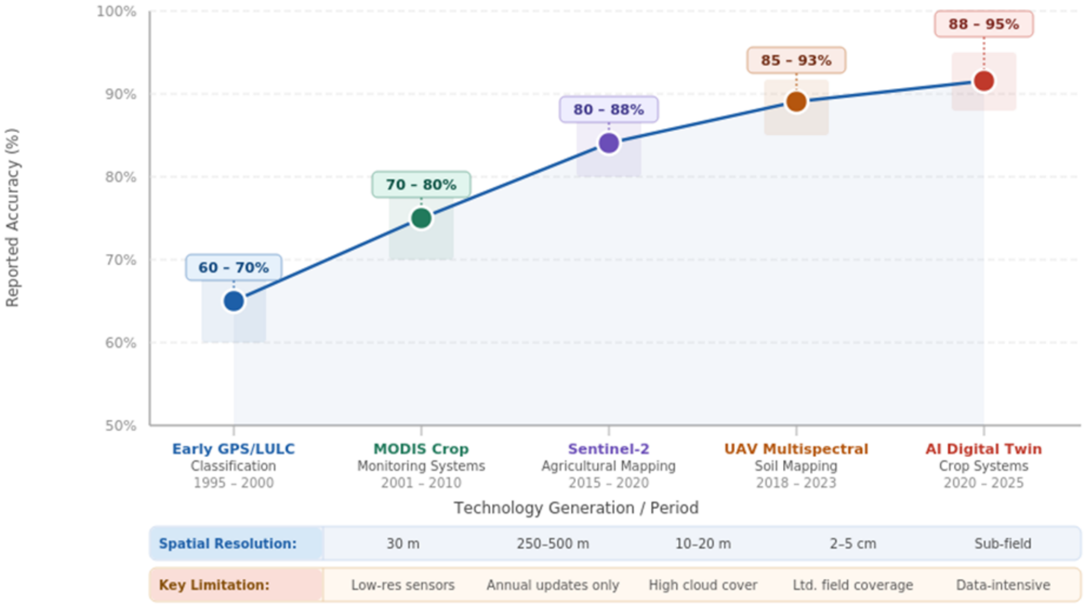

Figure 3. Precision Agriculture Digital Tool Accuracy Improvement (1995–2025) Reported accuracy range (%) across five technology generations. Data: **Table 2**, LMU Manuscript.

Table 2. Overview of Precision Agriculture Digital Tool Accuracy Trends and Validation Approaches.

Technology/Tool	Period(s)	Reported Accuracy	Resolution	Remarks
Early GPS-guided LULC Classification	1995–2000	~60–70%	30 m	Limited coverage, low-resolution sensors
MODIS Crop Monitoring Systems	2001–2010	~70–80%	250–500 m	Annual updates, regionally inconsistent
Sentinel-2 Agricultural Mapping	2015–2020	~80–88%	10–20 m	Improved revisit cycle, high cloud cover in tropics
UAV Multispectral Soil Mapping	2018–2023	~85–93%	2–5 cm	High resolution, limited field coverage
AI-based Digital Twin Crop Systems	2020–2025	~88–95% (near real-time)	Sub-field	Deep learning-enhanced, data-intensive

6. Agricultural Technology and Rural Land System Reform

6.1. Digital Tools in Land Tenure Documentation and Smallholder Land Rights

Digital technologies are becoming a very important aspect of improving land tenure records and securing smallholder land rights in a wide range of geographic and institutional settings. Digital land certification in Ethiopia helped to increase the creditworthiness of smallholder farmers by increasing access to land ownership data, lowering the cost of transactions, and motivating financial institutions to design specific loan products for small-scale agricultural producers [61]. Decentralised and transparent Blockchain technology provides a decentralised way of recording land rights in informal land markets, and is especially applicable in situations where formal registration systems have historically marginalised smallholder and customary tenure holders [62]. An idea of a blockchain-based land tenure system highlights the two-fold significance of legal and participatory governance, in which marginalised communities are substantively involved in digital land governance systems [64]. Empirical studies in China show that the application of digital technology greatly enhances agricultural land transfer-in, meaning that the better digital infrastructure is, the faster the agricultural modernisation and rural land market development will be achieved [61]. SmartSkeMa and other participatory digital documentation systems also enhance the traditional land tenure documentation by combining aerial images with community knowledge systems, which allows proper boundary demarcation and verification of rights at the grassroots.

6.2. Technology-Enabled Rural Revitalization Strategies

Rural revitalisation strategies have become a major policy response to rural decline, agricultural modernisation, and the attainment of common prosperity in developing economies, which are made possible by technology. Digitization of rural agricultural systems is critical to increasing agricultural productivity, improving farmers' livelihoods, and narrowing the urban-rural development gap. The general rural revitalisation policy of China focuses on extensive land system reform with the assistance of grassroots organisational development, investment in digital infrastructure and technology diffusion programmes that guarantee sustainable agricultural modernisation [13]. Digital technology can revitalise the rural areas in various overlapping channels, such as industrial revolution, rural talent, culture, ecological conservation, and optimisation of the governance system. Evidence has shown that technological advancement in agriculture has a positive effect on the rural revitalisation, land-scale operational reform and region-specific diffusion strategies are critical facilitators of successful technology-based rural development. Separation of land contracting and management rights is suggested as a complementary institutional framework to support large-scale agricultural activities, which addresses risks to migrant workers and encourages sustainable rural economic development [13].

6.3. Policy Frameworks Supporting Digital Agriculture in Rural Land Reform

The policy frameworks that are effective in promoting digital agriculture in the environment of rural land reform must be carefully designed to address the development of infrastructure, data governance, fair access, and alignment of institutions. In South Africa, the digital infrastructure transformation, data interoperability framework, and market compatibility structure are found to be the key to connecting the digitalisation initiatives to redistributive land reform programmes, thus promoting the inclusive agricultural modernisation [65]. In China, the prerequisites to the delivery of equitable dividends across rural communities by digital agriculture initiatives lie in the effective institutional supply, the ability to govern at the grassroots, and organisational embedding [66]. The Malaysian situation underscores the importance of holistic governance systems that would systematically deal with social and economic consequences such as data privacy, employment consequences, and digital literacy disparities, as well as foster sustainable and fair digital agriculture practices. West African countries such as Benin and Nigeria have prepared national digital agriculture roadmaps, in which the governance synergy across sectors is highlighted as a key factor in promoting digital agriculture and rural land reform agendas [65]. The just transition lens of agricultural digitalisation should also be examined based on social, economic, and environmental aspects, so that the policy frameworks are in line with the principles of equity and inclusiveness.

6.4. Equity and Access Considerations

The dimensions of equity and access are central to the need to make sure that the adoption of agricultural technologies and reforms in the rural land system create inclusive benefits. Existing land tenure systems in most emerging economies have documented barriers to the effective utilization of agricultural technologies because fragmented smallholder landholdings frequently fail to match the operational demands of precision farming systems, creating resource inefficiencies that disproportionately impact resource-constrained producers [67]. The introduction of new technologies like precision agriculture and blockchain offers great potential to streamline resources and broaden market access to smallholder farmers, but must be handled cautiously to prevent further widening of digital inequalities and ethical disparities [63]. They have cited stakeholder consultation and participatory governance as the pre-conditions to land reform programmes, and there is evidence to show that the lack of sufficient stakeholder involvement is a major setback to equitable program implementation and performance [68]. There is a need to have a systems-based reformation strategy that integrates property rights clarification together with the implementation of digital technology and inclusive financial services development to make sure that agricultural modernisation can be used to achieve sustainable development objectives without jeopardising the land rights and livelihoods of the vulnerable farming communities.

7. Barriers, Knowledge Gaps, and Future Research Directions

7.1. Technological, Institutional, and Socioeconomic Barriers to Adoption

The impediments to the implementation of agricultural technologies and innovative land management practices are complex and can be found on a technological, institutional, and socioeconomic level. In the context of soil reclamation in India, the high cost of the economic aspect, low level of technological knowledge, lack of administrative and extension services greatly discourage the involvement of the farmers in evidence-based reclamation practices [67]. The larger farming environment indicates systemic obstacles such as poor external economic situations, bureaucracies, poor market structures, and individual influences such as social isolation and financial stress that all hinder the uptake of technology within farming communities [69]. Among small-scale farmers in the context of IoT adoption, financial constraints, low digital skills, poor infrastructure, and lack of supportive policies are reported as the main socioeconomic obstacles, and future studies are suggested to aim at improving the digital literacy programmes and reinforcing the market access support [25]. The study of ICT adoption barriers in agriculture has found four categories of barriers that are overlapping and include economic, technical, social, and institutional barriers, which need to be mitigated by a concerted policy action. The next step in research should focus on context-specific barrier analysis and integrated stakeholder engagement approaches.

The cross-regional analysis shows that there are significant geographic trends in the occurrence and severity of technology adoption barriers. Financial constraints and lack of infrastructure on extension services are the leading barriers in South Asia and sub-Saharan Africa, with smallholder farmers not being able to afford precision agriculture hardware even in regions with mobile connectivity infrastructure [70,71]. On the other hand, the challenges in transitional economies in Central Asia and Eastern Europe are more likely to be more regulatory fragmentation, weak data governance systems and the inability of the state agricultural advisory systems to support technology integration on farm level. In Latin American contexts, intermediate forms can be seen, where cooperative farming models permit a certain amount of collective investment in precision farming equipment, but the lack of information security and the unequal access to digital literacy remain the limiting factors to mass adoption [72]. These regional differences highlight the importance of context-specific policy interventions that match the profile of each agricultural context, as opposed to technology-push policies that assume homogeneous conditions of adoption.

7.2. Knowledge Gaps in Long-Term Impact and Ecological Assessment Studies

There are still large knowledge gaps concerning the long-term ecological effects of precision agriculture and digital land management. There is a lack of systematic methodologies for impact assessment, especially in developing countries, and this is a key deficiency [13]. Long-term multi-stressor studies throughout the production cycle are needed for agroecological resilience studies [62]. Moreover, ecological risk assessment models have been found to have flaws in their ability to model multi-species interactions and to extrapolate laboratory results to ecosystem reality. A long-term research investment is needed to address these gaps, as is the development of standardised ecological monitoring protocols, and internationally coordinated interdisciplinary research programmes to provide policy-relevant evidence. There is also a need to further connect long-term ecological knowledge gaps to policy recommendations for sustainable land management in future research.

7.3. Recommendations for Interdisciplinary Research and Policy Co-Design

Successful interdisciplinary research and policy co-design has significant structural challenges such as disciplinary jargon, incompatibility of methods, institutional siloes, and deep-rooted epistemological divides that hinder fruitful collaboration between agricultural, technological, social, and governance research communities. The only way to overcome these impediments is by consciously nurturing inclusive research cultures, creating common conceptual languages that support effective cross-disciplinary dialogue, and by institutionalizing long-term collaborative research programmes [69]. Future studies ought to commit themselves to the development of refined transdisciplinary communication and co-production strategies, to new methodological architectures that can enable real integration of social sciences, humanities and technical fields in solving agricultural land management problems [13]. It is important to promote institutional commitment and sufficient allocation of resources in the long-term to maintain successful interdisciplinary work, especially because land management research is time-consuming and needs to produce strong evidence. Cooperative definition and methodical mapping of gaps in knowledge across disciplinary lines can significantly increase the relevance, adoption and applicability of research to policy and practice. Finally, actionable knowledge should be co-designed in multi-stakeholder processes that involve researchers, practitioners, policymakers, and farming communities to align knowledge with real-world land management requirements.

8. Integrated Framework and Policy Recommendations

8.1. Proposed Framework Aligning Agricultural Technology with Sustainable Land Management Goals

One of the major contributions and novel aspects of this review is the integrated framework proposed, which integrates digital technology adoption, land governance and SDG alignment into a single analytical architecture. This multidisciplinary architecture is needed to align technological innovation, policy design, economic incentives, and stakeholder governance to an integrated framework of achieving sustainable land management objectives and agricultural technology adoption. An underlying integrated system of sustainable agricultural land use and production processes highlights a multidisciplinary decision-making system that stresses the optimization of land-use types, the choice of the right agronomic inputs, and the application of irrigation methods that are tuned to the environmental profiles of vulnerability [11]. This practice requires that soil and plant conservation economics be aligned with sustainable policy design, stakeholder involvement processes, and novel economic models that mediate the achievement of productivity growth and the need to sustain the environment [11]. The technological innovations, such as precision agriculture systems, biotechnology applications, and AI-driven analytics, will be at the center of the proposed framework as they improve land-use efficiency and provide opportunities to achieve sustainable intensification to satisfy the increasing food demand without an equivalent increase in agricultural land [11]. An agent-based modeling approach goes on to show how technological advancements in agriculture can offer policymakers versatile tools for balancing economic growth and environmental conservation goals, such as creating networks of protected areas and productive agricultural landscapes [67]. Critical success factors of the framework are the need to deal with high technology adoption costs and regulatory barriers by providing specific policy support, public-private partnerships, and inclusive capacity-building programmes that guarantee equitable access to smallholder farmers.

The Framework of Evaluation of Sustainable Land Management (FESLM) recognizes five pillars of sustainability, such as productivity, security, protection, viability, and acceptability, as the criteria used to shape policy development and adaptive management. The proposed integrated framework requires actionable, evidence-based recommendations to be made to land administrators, policymakers, and agronomists to operationalize the proposed framework. To land administrators, priority investments must be made towards improved land market infrastructure, land information systems, and digitised cadastral records that will facilitate transparent, equitable, and efficient management of land resources [12]. Policymakers must ensure that policies related to water security, energy access, and agricultural land use are coherent within national development frameworks, so that land, water, and energy policies are structurally connected to enhance integrated resource management and human welfare [4]. Mainstreaming investment in digital agricultural innovations and rural infrastructure, especially in low-connectivity areas, should be a priority in sectoral policy portfolios to facilitate large-scale sustainable agricultural intensification. For agronomists, it is necessary to combine economic and social policy factors with technical advice to create truly sustainable agricultural systems, as the interactions among policy tools define overall system performance [12]. Planning in land-use should also encompass a wide range of policy tools such as fiscal incentives, industry support mechanisms and infrastructure planning to effectively deal with environmental degradation and geographical imbalances [4]. To continue the cause of responsible and intelligent land management, it is essential to enhance the quality of available data, increase the inclusivity of stakeholders, adaptive land administration models, and new information technologies to support the evidence-based decision-making process at each level of governance.

8.2. Actionable Recommendations for Land Administrators, Policymakers, and Agronomists

To realize resilient and equitable land-use systems, science-based targets, adaptive governance systems, and transformative technology pathways are to be integrated in line with global sustainable development commitments.

By creating a streamlined system of science-based indicators and target values, scenario analysis and policy development can be directed toward land-use systems that can help to achieve the SDGs by 2030 and beyond [4]. Extensive land-use governance systems should take into account the entire range of applicable policies- fiscal incentives, industry subsidies, and infrastructure planning, of environmental degradation and territorial inequalities by multiscale interventions. National-level land-use pathways provided by the FABLE Consortium show that sustainable land-use and food system change is possible, and that fundamental structural changes in each country are needed to achieve simultaneous SDG and Paris Agreement goals. The inclusion of spatial, temporal, and socioeconomic aspects of land-use modeling is essential to developing policies that capture the complexities of sustainable food provisioning and land governance at the local level and link local decision-making contexts with global sustainability models [73]. The new digital tools and socio-economic paradigms are becoming increasingly useful for recognizing and reinforcing sustainable land-use approaches, enabling the identification of leverage points in systemic change towards the 17 UN SDGs. It is suggested that a multi-sectoral, globally coordinated, cross-cutting analytical strategy, including food production, biodiversity conservation, carbon sequestration, and land degradation, is the best approach to achieving resilient and equitable land-use systems at both national and subnational levels [73].

8.3. Pathways toward Resilient and Equitable Land Use Systems

The careful combination of science-based targets, adaptive governance systems, and transformational digital technology trajectories is needed to achieve resilient and equitable agricultural land use systems in line with global sustainable development commitments. To convert these aspirations into practical practice requires a multi-sectoral, multi-world strategy that will respond to the needs of food production, biodiversity protection, carbon sequestration, and land degradation demands in unison [74,75]. The science-based indicators, including soil health standards, land productivity standards, and digital governance standards, provide the assessment basis for the scenario analysis and evidence-based policy development geared towards SDG realization by 2030 and beyond [4].

The design of resilient land-use pathways is guided by equity considerations. The customary land tenure holders, smallholder farmers, and marginalised farming communities have a disproportionate risk of land degradation caused by climate change and the least access to the digital technologies and financial instruments needed to construct an adaptive capacity [11,12]. The pathways should thus incorporate participatory governance systems that anticipate land rights, indigenous knowledge systems, and adaptive capacities of these communities into national land management systems. Precision agriculture technologies and digital tenure documentation tools can help align local choices with national sustainability goals without compromising community sovereignty over land resources [13].

On the macro-governance level, the integrated land use modelling with spatial, temporal, and socioeconomic dimensions is essential in the design of policies that reconcile the local decision-making environment with the global sustainability frameworks [74]. New digital technologies and data-driven socioeconomic models are playing an increasingly important role in identifying leverage points to transform the 17 UN Sustainable Development Goals at the systemic level. Operationalisation of the integrated framework suggested in this review, namely aligning the adoption of agricultural technology with the goals of sustainable land-use, inclusive governance, and science-based policy development, can help practitioners, policymakers, and land administrators to collectively progress towards agricultural land management systems that are productive, environmentally sustainable, and equitable at the same time [75].

Occupational wellbeing and safety of agricultural labour-force, such as heat stress, ergonomic risks, and health risks due to climate, is a critical, yet frequently neglected aspect of sustainable land management productivity, and evidence has shown that physiological limitations directly influence agricultural labour productivity and land use performance [76–79].

9. Conclusions

Despite the changes noted in this review, the present research has limitations and opportunities that may spur further research. The possibility of selection bias is one of the key limitations, as the review may have unconsciously favoured studies aligned with the current prevailing paradigms of precision agriculture. It can lead to biased inclusion of the existing literature and to an inability to address the full spectrum of attitudes towards specific issues of technology adoption. Therefore, further research might be conducted to address each thematic area represented in the analysis and discussion sections more methodologically.

Moreover, the quality of the included studies and their methodological heterogeneity can limit this review. In agricultural land management research in the digital age, where research methods and data sources vary across institutional and national contexts, the validity and comparability of results may be difficult to assess across studies. This is capable of deeming the review's usefulness for making very specific, context-conditioned policy prescriptions. Moreover, although this narrative review is a versatile tool for generalising modern research, it might not be entirely accurate when considering the latest technological advances, as the fields of precision agriculture and digital land management science are changing rapidly. Future research directions might explore the performance validation techniques of automated technology based on crowd-sourced field information, multi-sensor fusion, and machine learning to enable scalable, robust precision agriculture evaluation. Also, the use of standardized procedures for benchmarking digital agricultural technology performance may significantly enhance uniformity and comparability across the entire research literature.

Author Contributions

Conceptualization, methodology, formal analysis data, visualization, writing-original draft preparation, G.P.; writing-review and editing, supervision, A.J., S.B.K., and P.M. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding. The authors declare that no specific grant from any funding agency in the public, commercial, or not-for-profit sectors was received for this review.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets and analytical outputs used in this study are provided in the main text. Additional data may be made available upon reasonable request to the corresponding author.

Acknowledgments

The authors wish to express their sincere gratitude to the handling editor and anonymous reviewers for their constructive feedback and valuable suggestions, which substantially improved the quality and clarity of this manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

We confirm that no AI-assisted writing aids have been utilized in the writing of this paper.

References

1. Atanassov, A.; Abumhadi, N. Major challenges facing the global food and agricultural system in the 21st century. In *CAB International*; CAB International: Wallingford, UK, 2012; pp. 211–228.
2. Késmárki-Gally, S.; Fenyvesi, L. Tendencies and challenges in global agriculture. *Probl. World Agric.* **2012**, *12*, 37–45. [CrossRef]
3. Borah, A.; Sahu, S.; Srivastava, R.P.; et al. Exploring the economic challenges threatening global agriculture

and food security. *Ecol. Environ. Conserv.* **2024**, *30*, S193–S199. [CrossRef]

4. Smith, P. Managing the global land resource. *Proc. R. Soc. B Biol. Sci.* **2018**, *285*, 20172798. [CrossRef]
5. Wilkin, J. International Agricultural Land use Conditions. *Zesz. Nauk. SGGW Ekon. Organ. Gospod. Zywnosc.* **2015**, *15*, 154–160. Available online: https://bazekon.uek.krakow.pl/en/rekord/171404221
6. Panotra, N.; Deepika, R.B.; Roy, P.; et al. Advances in precision agriculture: A review of technologies, applications and future prospects. *Arch. Curr. Res. Int.* **2025**, *25*, 722–737. [CrossRef]
7. Adewuyi, A.Y.; Anyibama, B.; Adebayo, K.B.; et al. Precision agriculture: Leveraging data science for sustainable farming. *Int. J. Sci. Res. Arch.* **2024**, *12*, 1122–1129. [CrossRef]
8. Tangkesalu, D.; Tiekink, E.R.T.; Tooy, D.; et al. Precision agriculture: Integrating technology for enhanced efficiency and sustainability in crop management. *Glob. Sci. J.* **2023**, *1*, 213–219. [CrossRef]
9. Pal, G.; Roy, S.; Bag, J.K.; et al. A comprehensive review of ML and optimization techniques in agricultural system modeling: A cybernetics perspective. *Comput. Electron. Agric.* **2026**, *241*, 111188.
10. Anshu, M.; Kumar, S. Precision agriculture and digital innovations in soil management. In *Current Trends in Soil Science: Challenges and Innovations for Effective Ecosystem Management V4B30*; Iterative International Publishers: New Delhi, India, 2024; pp. 150–159. [CrossRef]
11. Xie, C. The role of modern agricultural technologies in improving agricultural productivity and land use efficiency. *Front. Plant Sci.* **2025**, *16*, 1675657. [CrossRef]
12. Prokopenko, N.I.; Dets, T.; Rozhi, T. Land planning and management of land tasks within agricultural projects: Successful practices and challenges. *Urban Plan. Territ. Plan.* **2024**, *86*, 462–476. (in Ukrainian) [CrossRef]
13. Sunarko, S. Satellite-guided decision support systems for sustainable land management: A cross-regional approach to crop monitoring and resource optimization. *Agric. Power J.* **2024**, *1*, 39–50. [CrossRef]
14. Rodríguez, D.T.G.; Martínez Ramírez, C.D.; Hernandez, J. Public management and agricultural sciences: Innovation, governance and sustainability in the agricultural sector. *Punto de Vista* **2025**, *16*, 1–14. (in Spanish) [CrossRef]
15. Belokopytov, A.V.; Moskaleva, N.V.; Matveeva, E. Management and rational use of land resources in agriculture. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *979*, 012022. [CrossRef]
16. Dey, P.; Mahapatra, B.S.; Mitra, B.; et al. Potential nexus approach for sustainable soil productivity resource management. In *Environmental Nexus for Resource Management*; CRC Press: Boca Raton, FL, USA, 2024; pp. 243–273.
17. Ünver, O.; Mansur, E. Land and water governance, poverty, and sustainability. In *Sustainable Food and Agriculture: An Integrated Approach*; Elsevier: Amsterdam, The Netherlands, 2019. [CrossRef]
18. Georgescu, L.P.; Balsalobre-Lorente, D.; Zlati, M.L.; et al. Cluster Analysis of the Transition to Climate Neutrality in the European Union. *Sustain. Dev.* **2025**, *33*, 1498–1519. [CrossRef]
19. De Rosa, M.; Knudsen, M.T.; Hermansen, J.E. A comparison of Land Use Change models: Challenges and future developments. *J. Clean. Prod.* **2016**, *113*, 183–193.
20. Iukhno, A. The Land Resources Management According to Agrarian Land Zoning: Land Resources Management. *Mod. Manag. Rev.* **2023**, *28*, 39–49. [CrossRef]
21. Khose, S.B.; Mailapalli, D.R. Spatial mapping of soil moisture content using very-high resolution UAV-based multispectral image analytics. *Smart Agric. Technol.* **2024**, *8*, 100467.
22. Kayastha, S.; Behera, A.; Sahoo, J.P. Growing green: Sustainable agriculture meets precision farming: A review. *Bhartiya Krishi Anusandhan Patrika* **2024**, *38*, 349–355. [CrossRef]
23. Borovyi, V.; Braslavska, O.; Rozhi, T. Satellite and UAV imaging as tools for monitoring land resources: Modern technologies and their application in Ukraine. *Tehnichni nauky ta tekhnolohii* **2025**, *1*, 315–327. (in Ukrainian) [CrossRef]
24. Meshram, P.G.; Shaniware, Y.; Bhondave, G.P. Precision agriculture: UAV-based soil mapping and remote sensing applications. *Asian Res. J. Agric.* **2024**, *17*, 885–891. [CrossRef]
25. Zhu, W.; Rezaei, E.E.; Nouri, H. Quick detection of field-scale soil comprehensive attributes via the integration of UAV and Sentinel-2B remote sensing data. *Remote Sens.* **2021**, *13*, 4716. [CrossRef]
26. Hoque, A.; Padhiary, M.; Roy, S. Precision agriculture meets sustainable chemistry. In *Sustainable Chemistry and Pioneering Green Engineering Solutions*; IGI Global: Hershey, PA, USA, 2025. [CrossRef]
27. Pal, G. Conservation Agriculture and Its Mechanization. In *Advances in Agriculture Sciences*; AkiNik Publications: New Delhi, India, 2017.
28. Agbonika, D.A.; Abah, E.O.; Fidelis, E.S. A systematic review of management science integration in farm decision tools: Advancing theory for agricultural problem-solving. *Int. J. Multidiscip. Res. Growth Eval.* **2025**, *6*, 656–664. [CrossRef]

29. Akbar, A.S.I.; Shah, S.A.A.; Tabassum, S. Integrating physics-based models, mathematical optimization, and statistical analytics for advancing precision agriculture and sustainable farming practices. *Crit. Rev. Soc. Sci. Stud.* **2025**, *3*, 291–302. [CrossRef]
30. Farooqi, Z.U.R.; Ayub, M.A.; Nadeem, M.A. Precision Agriculture to Ensure Sustainable Land Use for the Future: Precision Agriculture and Arable Land Use. In *Examining International Land Use Policies, Changes, and Conflicts*; IGI Global: Hershey, PA, USA, 2021. [CrossRef]
31. Raihan, A. A systematic review of Geographic Information Systems (GIS) in agriculture for evidence-based decision making and sustainability. *Glob. Sustain. Res.* **2024**, *3*, 1–24.
32. Arseni, M.; Rosu, A.; Calmuc, M.; et al. Development of flood risk and hazard maps for the lower course of the Siret River, Romania. *Sustainability* **2020**, *12*, 6588. [CrossRef]
33. Nagarajan, R.; Ajith, B.S.; Praveen, R.K. Real-time monitoring of agricultural land with crop prediction and animal intrusion prevention using IoT and machine learning at edge. In Proceedings of the 2020 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT), Bangalore, India, 2–4 July 2020. [CrossRef]
34. Rathore, N.S.; Joshi, S.; Choudhary, N. *Digital Technologies for Agriculture*; Nipa Genx Electronic Resources & Solutions Pvt Ltd.: New Delhi, India, 2022. [CrossRef]
35. Srivastava, R. Applications of remote sensing in land resource inventory and mapping. In *Geospatial Technologies in Land Resources Mapping, Monitoring and Management*; Springer: Cham, Switzerland, 2018. [CrossRef]
36. Patil, B.P.; Asra, S. Smart IoT-driven precision irrigation: Enhancing water efficiency with machine learning and real-time environmental monitoring. In Proceedings of the 2025 International Conference on Computing Technologies & Data Communication (ICCTDC), Hassan, India, 4–5 July 2025. [CrossRef]
37. Kaur, R.; Nehra, D.; Bhushanwar, K. Enhancing sustainability, climate resilience, and resource efficiency with IoT-based precision agriculture. *J. Sustain. Agric. Technol.* **2025**, *2*, 364–371. [CrossRef]
38. Kumar, K.P.; Manjula, S. Unlocking water conservation: Synergizing IoT and machine learning for agricultural irrigation efficiency. In Proceedings of the 2024 International Conference on Knowledge Engineering and Communication Systems (ICKECS), Chikkaballapur, India, 18–19 April 2024. [CrossRef]
39. Tejas, V.; Vishaal, K.; Sudeep, G.; et al. Intelligent precision farming with an eco-conscious smart irrigation system. *Int. J. Res. Appl. Sci. Eng. Technol.* **2024**, *12*, 952–955. [CrossRef]
40. Kota, R.M.C.; Susheel, A.; Chaganti, B.P.R. ML assisted smart watering system with IoT for cloud-based precision agriculture. In Proceedings of the 2024 IEEE Region 10 Symposium (TENSYMP), New Delhi, India, 27–29 September 2024. [CrossRef]
41. Chandrappa, V.Y.; Islam, N.; Ashwath, N. Enhancing IoT-based smart irrigation efficiency through optimized sensor placement, noise elimination, and incremental learning. In *Intelligent Internet of Everything for Automated and Sustainable Farming*; IGI Global: Hershey, PA, USA, 2025. [CrossRef]
42. Ghilan, A.; El Afou, Y.; Merras, M. Data-driven precision agriculture advanced irrigation system for sustainable smart farming. In Proceedings of the 2024 4th International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET), Fez, Morocco, 16–17 May 2024. [CrossRef]
43. Karn, S.; Kotecha, R.; Pandey, R.K. Towards sustainable farming: Leveraging AIoT for precision water management and crop yield optimization. *Procedia Comput. Sci.* **2024**, *233*, 772–781. [CrossRef]
44. Shaheb, M.R.; Sarker, A.; Shearer, S.A. *Precision Agriculture for Sustainable Soil and Crop Management*; IntechOpen: London, UK, 2022. [CrossRef]
45. Chaudhari, S.; Patra, A.K.; Dey, P.K.; et al. Sensor based monitoring for improving agricultural productivity and sustainability: A review. *J. Indian Soc. Soil Sci.* **2022**, *70*. [CrossRef]
46. Sunil, T.; Pachiappan, K.; Senthilrajan, S.; et al. Integration of convolutional neural networks for real-time monitoring of soil health in precision agriculture. In Proceedings of the 2024 8th International Conference on Electronics, Communication and Aerospace Technology (ICECA), Coimbatore, India, 6–8 November 2024. [CrossRef]
47. Bentham, H.; Harris, J.A.; Birch, P.; et al. Habitat classification and soil restoration assessment using analysis of soil microbiological and physico-chemical characteristics. *J. Appl. Ecol.* **1992**, *29*, 711–718.
48. Sindhushree, T.S.; Kavya, D.; Jitendra, G.H.; et al. Digital soil mapping: A review of techniques, applications and emerging trends. *J. Sci. Res. Rep.* **2025**, *31*, 1151–1158. [CrossRef]
49. Zhou, J.; Xu, Y.; Gu, X. High-precision mapping of soil organic matter based on UAV imagery using machine learning algorithms. *Drones* **2023**, *7*, 290. [CrossRef]
50. Molin, J.P.; Bazame, H.C.; Maldaner, L.F. Precision agriculture and the digital contributions for site-specific management of the fields. *Rev. Cienc. Agron.* **2020**, *51*. [CrossRef]

51. Blann, K.L.; Anderson, J.L.; Sands, G.R.; et al. Effects of agricultural drainage on aquatic ecosystems: A review. *Crit. Rev. Environ. Sci. Technol.* **2009**, *39*, 909–1001.
52. Rani, H.V.; Kakkar, P.; Singh, D.P. Advancements in precision agriculture for maximizing crop yield and minimizing waste via innovative technological solutions. *Green Chem. Technol.* **2025**, *2*. [CrossRef]
53. Meesala, H.; Brunori, G. Dynamics of using digital technologies in agroecological settings: A case study approach. *Agriculture* **2025**, *15*, 1636. [CrossRef]
54. Farooqi, Z.U.R.; Ayub, M.A.; Nadeem, M.; et al. Precision Agriculture to Ensure Sustainable Land Use for the Future: Precision Agriculture and Arable Land Use. In *Research Anthology on Strategies for Achieving Agricultural Sustainability*; IGI Global: Hershey, PA, USA, 2022. [CrossRef]
55. Duff, H.; Hegedus, P.B.; Loewen, S.; et al. Precision agroecology. *Sustainability* **2022**, *14*, 106. [CrossRef]
56. Hallett, S.H.; Sakrabani, R.; Keay, C.A.; et al. Developments in land information systems: Examples demonstrating land resource management capabilities and options. *Soil Use Manag.* **2017**, *33*, 514–529. [CrossRef]
57. Diaz-Gonzalez, F.A.; Correa-Florez, C.A.; Vuelvas, J.; et al. A methodology for estimating soil quality indicators in agricultural systems using UAV and machine learning. In Proceedings of the 2022 12th Workshop on Hyperspectral Imaging and Signal Processing: Evolution in Remote Sensing (WHISPERS), Rome, Italy, 13–16 September 2022. [CrossRef]
58. Eskandari, R.; Mahdianpari, M.; Mohammadimanesh, F.; et al. Meta-analysis of UAV imagery for agro-environmental monitoring using machine learning and statistical models. *Remote Sens.* **2020**, *12*, 3511. [CrossRef]
59. Sharma, U.; Maheshwari, S.; Kamal, M.A. Industrial land suitability analysis for Aligarh District using GIS-based multi-criteria evaluation (MCE) technique. *Archit. Eng. Sci.* **2025**, *6*. [CrossRef]
60. Mathenge, M.; Sonneveld, B.G.; Broerse, J.E. Application of GIS in agriculture in promoting evidence-informed decision making for improving agriculture sustainability: A systematic review. *Sustainability* **2022**, *14*, 9974. [CrossRef]
61. Çullu, M.A.; Bilgili, A.; Aydemir, A.; et al. A GIS Based Land Suitability and Gross Value Evaluation of Mined Lands in Şanlıurfa District. *J. Agric. Sci.* **2022**, *28*. [CrossRef]
62. Purwaamijaya, I.M. Land suitability evaluation for housing and residential based on GIS, satellite imagery and DTM. In Proceedings of the 7th Mathematics, Science, and Computer Science Education International Seminar, Bandung, Indonesia, 12 October 2020. [CrossRef]
63. Vijaykumar, J.R.; Thirumal, T.K. Application of remote sensing and GIS for real-time crop monitoring and extension support services. *Int. J. Environ. Clim. Change* **2025**, *15*. [CrossRef]
64. Pal, G.; Patel, T. Physiological responses to heat stress in rice transplanting workers in Northeast India and work-rest schedule recommendations. *Work* **2025**, *83*, 1–13. [CrossRef]
65. Pal, G.; Patel, T.; Banik, T. Effect of climate change associated hazards on agricultural workers and approaches for assessing heat stress and its mitigation strategies. *Int. J. Curr. Microbiol. App. Sci.* **2021**, *10*, 2947–2975.
66. Patel, T.; Pal, A.; Pal, G.; et al. Effects of WBGT on the thermal and physiological responses of north-eastern Indian agricultural workers during paddy transplanting operations. *Indian J. Hill Farm.* **2024**, *37*, 36–48.
67. Rajkumar, M.; Kumar, T.A.; Kanimozhi, P.; et al. Sustainable farming with AI-driven yield prediction models and real-time IoT sensor data. In Proceedings of the 2025 6th International Conference for Emerging Technology (INCET), Belgaum, India, 23–25 May 2025. [CrossRef]
68. Georgescu, P.L.; Barbuta-Misu, N.; Zlati, M.L.; et al. Quantifying the performance of European agriculture through the new European sustainability model. *Agriculture* **2025**, *15*, 210. [CrossRef]
69. Pal, G. Renewable Energy for Climate Change Mitigation. In *Advances in Renewable Energy Engineering*; Narendra Publishing House: New Delhi, India, 2021.
70. Kuli, B.K.; Debnath, J.C.; Sheikh, A. Smart farming revolution: AI, IoT, and robotics in precision agriculture and soil conservation. *Int. J. Sci. Res. Sci. Eng. Technol.* **2025**, *12*. [CrossRef]
71. Bhat, R.A.; Malik, K.M.; Raina, F.A.; et al. Integrating Conservation Agriculture with Precision Farming for Improved Yield Stability. *J. Food Biotechnol.* **2024**, *5*. [CrossRef]
72. Getahun, S.; Kefale, H.; Gelaye, Y. Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. *Sci. World J.* **2024**, *2024*, 2126734. [CrossRef]
73. Rajeswari, D.; Athish, V.P.; Ponnusamy, S. Digital twin-based crop yield prediction in agriculture. In *Harnessing AI and Digital Twin Technologies in Businesses*; IGI Global: Hershey, PA, USA, 2024. [CrossRef]
74. Sarfo, I.; Effah, N.A.A.; Djan, M.A.; et al. Challenges and pathways for sustainable development in global land use systems: A narrative review. *Land Manag. Util.* **2025**, *1*, 1474. [CrossRef]
75. Gao, L.; Bryan, B.A. Finding pathways to national-scale land-sector sustainability. *Nature* **2017**, *544*, 217–

222. [CrossRef]
76. Pal, G.; Patel, T.; Singh, H.D.; et al. Bluetooth module-based wearable heatstroke alert system based on physiological and environmental parameters for agricultural workers. *Res. J. Agric. Sci.* **2022**, *13*, 1388–1395. [CrossRef]
77. Singh, H.J.; Pal, G.; Singh, H.D.; et al. Ergonomic evaluation of different paddy threshing methods in Meghalaya. *J. Krishi Vigyan* **2024**, *12*, 521–530.
78. Pal, G.; Patel, T. Heat Stress's Impact on Agricultural Worker's Health, Productivity, and its Effective Prevention Measures: A Review and Meta-Analysis. *Int. J. Agric. Syst.* **2021**, *9*, 51–79.
79. Pal, G.; Biswas, A.; Bairagya, N.D.; et al. Climate change, environmental degradation, and smart and sustainable systems. In *Climate Change and Environmental Degradation*; Apple Academic Press: Palm Bay, FL, USA, 2024.