Smart Intercropping Systems: A Critical Review of IoT, AI, and Climate-Smart Agricultural Integration for Sustainable Food Production

Muhilan Mahendhiran[1*], DVS Bhagavanulu[2] and Prabhaharan Renganathan[3*]

[1]*Department of Agri-Business Management, Faculty of Agriculture, Vivekananda Global University, Jaipur, Rajasthan, India*

[2]*Vivekananda Global University, Jaipur, Rajasthan, India*

[3]*Department of Bioecology and Biological Education, M. Akmullah Bashkir State Pedagogical University, Ufa, Russia*

*Corresponding author: prabhaharan06@gmail.com

Abstract

The global population, currently estimated at approximately 8.2 billion, is projected to reach nearly 10 billion by 2050, necessitating significant enhancements in agricultural productivity under limited cultivable land. However, monocropping systems have contributed to soil and water degradation, excessive dependence on synthetic fertilizers and pesticides, and a decline in soil fertility. Moreover, anthropogenic greenhouse gases (GHGs) are expected to reduce global agricultural productivity by up to 15.9% by 2080. Therefore, sustainable food production requires ecologically balanced and resource-efficient systems. In this context, intercropping systems provide a resilient approach through enhanced yield stability, improved resource-use efficiency, biological nitrogen fixation, and suppression of pests and weeds. This structured review critically synthesizes recent advances in intercropping systems integrated with climate-smart agriculture (CSA), the Internet of Things (IoT), artificial intelligence (AI), precision agriculture, and energy-smart agricultural technologies for sustainable and resilient food production. Relevant literature published between 2010 and 2025 was analyzed to evaluate the ecological, technological, and sustainability outcomes associated with smart intercropping systems. Specifically, the analysis encompassed IoT-based monitoring systems, AI-driven decision support frameworks, precision irrigation, nutrient management, and carbon-smart farming practices. This review highlights that integrating ecological intercropping principles with digital agricultural technologies enhances soil health, climate resilience, input-use efficiency, and farm sustainability while supporting sustainable intensification and Agriculture 4.0.

Keywords: sustainable development goals (SDGs), food security, precision agriculture

B. Choudhary and V. V. Singh (eds.), *Proceedings of the Anubhuti 4.0: Discourses in Indian Knowledge Systems – Pathways of Culture, Inclusion, and Sustainability (ICIKS 2026)*, Advances in Social Science, Education and Humanities Research 1030,
https://doi.org/10.2991/978-2-38476-615-4_31

1. Introduction

Climate change is a rapidly intensifying global challenge, and the agricultural sector functions as both a contributor and a highly vulnerable system that directly influences food markets and supply chains [1]. Furthermore, food security, global livelihoods, environmental stability, and sustainable agricultural production depend on climate regulation mechanisms [2]. The integration of intercropping systems with sustainable practices and advanced technologies could be a potential pathway for mitigating climate-induced agricultural risks [3]. The global population is projected to reach approximately 10 billion by 2050, with over two billion people, particularly in developing regions, likely to experience food insecurity, including hidden hunger associated with deficiencies in proteins, vitamins, and essential micronutrients [4-7]. Moreover, approximately 80% of the arable land is already under cultivation; therefore, further increases in production must depend on resource use optimization through technological interventions [2]. Food security, with limited land and declining freshwater resources, remains a critical global challenge. Additionally, global food demand is expected to increase by 50–70% by 2050, whereas climate-induced yield reductions in staple crops, such as wheat and maize, may reach 10–25% under high-emission scenarios, intensifying the pressure on agricultural systems [4].

Reducing greenhouse gas (GHG) emissions is essential for climate mitigation, ecosystem conservation, and biodiversity protection [8]. Climate-smart agriculture (CSA) facilitates sustainable food production while addressing climate risks, and contributes to Sustainable Development Goal 2 (zero hunger), which promotes resilient and inclusive agricultural systems [9,10]. Furthermore, intercropping systems provide a strategic approach to sustainable agriculture and food security while reducing anthropogenic environmental degradation [8,11]. Recent advances in smart farming have demonstrated the adoption of artificial intelligence (AI) for data-driven automated decision-making. Moreover, supporting technologies, such as the Internet of Things (IoT), remote sensing, variable-rate technology (VRT), and machine learning (ML), facilitate precision-based and resource-efficient agricultural management [4]. Additionally, emerging systems, including aquaponics, vertical farming, aeroponics, and fogponics, have enhanced nutrition-sensitive production, whereas degraded soils can be restored through organic amendments [6]. Integrated farming systems (IFS), including interactions among soil, water, crops, and livestock, represent efficient approaches for resource recycling and waste minimization [12]. However, despite extensive research on intercropping, climate-smart agriculture, and precision farming technologies, existing review studies have predominantly evaluated the ecological and technological dimensions independently. Most available studies focus either on the agronomic benefits of intercropping systems or on the technological advancements associated with AI- and IoT-enabled precision agriculture, with limited emphasis on their integrated application in climate-resilient and resource-efficient agricultural systems. Furthermore, a critical synthesis of the interactions among ecological intensification, digital agriculture, and energy-smart agricultural practices across diverse agroecosystems remains insufficient. Consequently, a comprehensive and integrated framework linking intercropping systems with CSA, IoT-enabled monitoring, AI-driven decision support systems, and sustainable intensification strategies is required to support resilient agricultural transformation [8,11].

Therefore, future agricultural systems must integrate ecological intensification with digital innovations to simultaneously improve productivity, optimize resource utilization and strengthen climate resilience. In this context, the integration of intercropping with IoT-enabled monitoring and AI-driven decision-making enhances productivity, optimizes input use, and improves resilience compared with monocropping systems. Accordingly, the objective of this review is to critically synthesize recent advances in smart intercropping systems integrated with climate-smart agriculture, AI, IoT, precision agriculture, and energy-smart agricultural technologies. In addition, this review evaluates the ecological, technological, and sustainability outcomes associated with these integrated systems, while identifying current research gaps, technological limitations, and implementation challenges affecting large-scale adoption, particularly in developing-country agricultural systems.

2. Review Methodology

This review adopted a structured narrative review approach to critically synthesize recent advances in intercropping systems integrated with climate-smart agriculture (CSA), the Internet of Things (IoT), artificial intelligence (AI), precision agriculture, and energy-smart agricultural technologies. Relevant literature published between 2010 and 2025 was systematically retrieved from major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed, and Google Scholar.

The literature search was conducted using combinations of the following keywords and Boolean operators: “intercropping,” “climate-smart agriculture,” “smart farming,” “precision agriculture,” “Internet of Things,” “IoT,” “artificial intelligence,” “machine learning,” “energy-smart agriculture,” “digital agriculture,” “sustainable intensification,” and “food security.” Additional studies were identified by cross-referencing relevant review articles and citation tracking.

Studies were included if they (i) addressed intercropping or climate-smart agricultural systems; (ii) evaluated digital or precision agricultural technologies associated with crop production systems; (iii) reported outcomes related to productivity, resource-use efficiency, climate resilience, sustainability, or energy optimization; and (iv) were published in peer-reviewed journals or authoritative institutional reports. Studies lacking methodological clarity, unrelated to agricultural systems, or focused exclusively on nonagricultural engineering applications were excluded from the review.

The retrieved literature was critically evaluated and thematically categorized into major areas, including climate-smart agriculture, ecological mechanisms of intercropping, IoT- and AI-enabled precision systems, energy-smart agriculture and sustainability outcomes. Quantitative findings reported across studies were comparatively synthesized to identify emerging trends, technological opportunities, implementation constraints, and research gaps relevant to sustainable and resilient food production systems.

3. Climate-Smart Agriculture (CSA): Principles, Mechanisms, and Agricultural Significance

CSA is a holistic framework that integrates digital and non-digital interventions to enhance agricultural productivity, farm income, climate resilience and environmental sustainability [13]. Studies have demonstrated that CSA adoption increases crop yields by 27.5% and farm income by 31.2%, while resulting in carbon sequestration of 2.5–3.6 t ha^{-1} yr^{-1}, which enhances agroecosystem sustainability [14]. Furthermore, CSA, promoted by the Food and Agriculture Organization (FAO), aims to reduce GHG emissions while ensuring sustainable agricultural development [15]. The large-scale adoption of CSA practices enhances agricultural productivity by 29–126%, depending on agroecological conditions, indicating its transformative potential in climate-resilient systems [16]. However, the magnitude of the CSA-associated benefits varies substantially depending on the climatic conditions, crop systems, farm scale, technological accessibility, and management intensity [13,17,18]. For example, higher productivity gains are frequently reported in intensively managed systems with improved irrigation and nutrient management infrastructure, whereas resource-limited smallholder systems often exhibit lower technological adoption capacity despite significant potential benefits to the farmers [14,17,20]. Key stakeholders, including farmers, producers, policymakers, researchers, and institutions, facilitate knowledge transfer, technological diffusion and policy execution [17]. CSA implementation comprises five core components: (i) evidence-based approaches, (ii) enabling policies, (iii) institutional support, (iv) financial mechanisms, and (v) field-level strategies, which ensure scalability and long-term sustainability [15].

In addition, CSA optimizes the use of critical resources, including water, soil, agrochemicals, and energy, thereby minimizing losses and environmental degradation [6]. Consequently, resource use efficiency under CSA improves by approximately 48%, reinforcing its role in sustainable intensification (SI) [18]. Furthermore, CSA serves as a viable alternative to energy-intensive practices such as intensive tillage, excessive fertilization, and inefficient irrigation in cereal-based systems [19]. Notably, integrated CSA adoption increased crop yield by 43% and farm income by 71%, confirming its economic viability [18]. In addition, SI is intrinsically associated with CSA and enhances food and nutritional security [20]. Intercropping is a key non-digital CSA strategy integrated with crop diversification, organic residue recycling, and sustainable grassland management [21]. Consequently, intercropping-based CSA systems achieve yield advantages exceeding 25% along with improved soil fertility and pest suppression, indicating strong ecological and economic benefits [22]. Nevertheless, the effectiveness of intercropping-based CSA systems remains context-dependent because crop compatibility, environmental variability, soil fertility status, and agronomic management strongly influence the system performance. Moreover, long-term field-scale assessments evaluating the combined ecological and socioeconomic impacts of CSA-based intercropping systems remain comparatively limited, particularly under developing-country agricultural conditions [15,20,21].

The integration of CSA with intercropping represents a critical pathway for SI, wherein intercropping enhances biodiversity, nutrient cycling, and resilience, and digital technologies such as IoT and AI facilitate real-time monitoring and precision input management [20]. Furthermore, IoT-enabled systems reduce operational costs by up to 30% while improving efficiency, thereby strengthening the technological dimension of CSA-based intercropping [23]. However, despite the increasing integration of digital technologies within CSA frameworks, large-scale implementation remains constrained by infrastructural limitations, high investment costs, digital illiteracy, interoperability challenges, and unequal access to advanced technologies among smallholder farming communities in developing countries [13,17]. Therefore, future CSA-based smart intercropping systems should prioritize scalable, low-cost, and region-specific technological solutions to facilitate inclusive and sustainable agricultural transformations. The conceptual integration of intercropping systems with climate-smart agriculture and digital technologies is shown in Fig. 1, highlighting a synergistic framework for enhancing productivity, resource-use efficiency, and climate resilience.

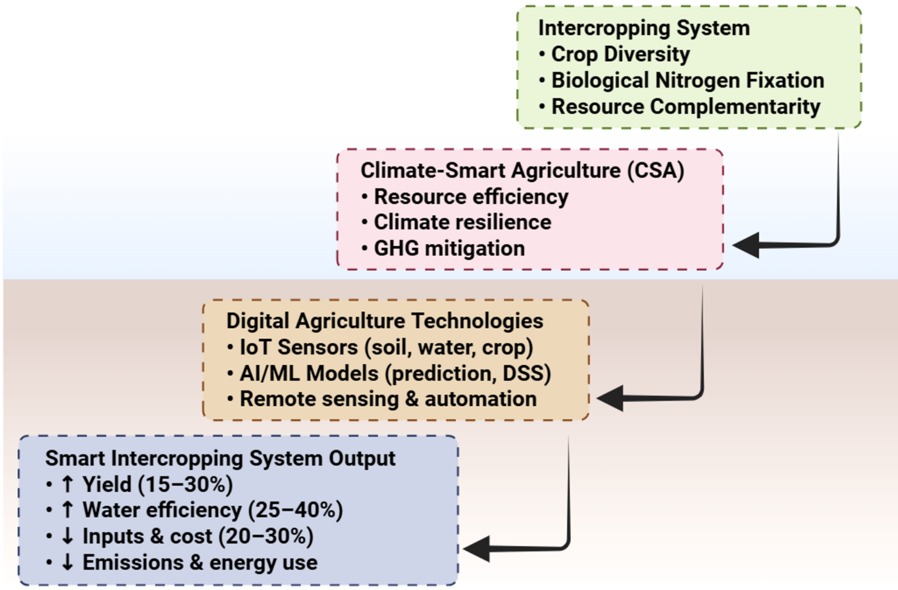

Fig. 1. An integrated framework of smart intercropping systems combines ecological processes, climate-smart agriculture (CSA), and digital technologies (Internet of Things and artificial intelligence) for sustainable and resilient food production.

4. Intercropping Systems: Ecological Mechanisms, Resource Optimization, and Productivity Enhancement

Intercropping systems are scientifically robust farming systems that involve the cultivation of two or more crops within defined spatial or temporal arrangements [3]. Notably, these systems require relatively low external inputs and enhance agroecosystem function through increased biodiversity and ecological interactions. The primary objective is to maximize interspecific facilitation while minimizing competitive interactions, which improves plant growth and system productivity [24]. Intercropping operates through niche differentiation, resource complementarity, and facilitative interactions among component crops. Specifically, differences in root architecture facilitate the vertical stratification of nutrient uptake, with deep-rooted crops accessing subsoil nutrients and shallow-rooted crops exploiting topsoil resources, thereby enhancing nutrient acquisition efficiency [25]. Furthermore, temporal complementarity in growth patterns facilitates the efficient utilization of light, water, and nutrients at different growth stages, thereby reducing competition and improving resource-use efficiency. Additionally, legume-based systems facilitate biological nitrogen fixation, reduce dependence on synthetic fertilizers, and improve soil fertility [3]. Moreover, rhizosphere interactions, including root exudation and microbial symbiosis, enhance nutrient solubilization, soil biological activity and stress resilience [26]. These ecological mechanisms contribute to sustainable intensification by improving productivity while minimizing environmental degradation and external input dependency [3,24].

Intercropping is widely adopted for food crop production in tropical regions (e.g., India), whereas in temperate regions (e.g., the United Kingdom), it is primarily utilized for forage-based systems [27]. However, optimizing intercropping systems under diverse agro-climatic conditions remains a major challenge. This challenge is particularly pronounced in regions with erratic rainfall and low soil fertility, where climate variability increases crop vulnerability [28]. Recent large-scale European trials have demonstrated that cereal–legume intercropping achieves 30% higher yields than monocropping under field conditions, indicating strong scalability [29]. Moreover, global meta-analyses have reported average maize yield increases of 4.5 %, with gains up to 8.1% in Asia, particularly in legume-based systems [30]. Additionally, intercropping enhances crude protein yield by 36.7% and nitrogen-use efficiency by 40.3%, which improves both nutritional output and input efficiency [31]. Furthermore, optimized intercropping–fertilization combinations have achieved yield increases of up to 35.1% compared to sole cropping [32]. Notably, intercropping significantly enhances yield stability and reduces the probability of crop failure (e.g., once in 36 years compared to frequent failures in monocropping systems) [3]. However, the magnitude of these benefits varies substantially depending on the crop combinations, climatic conditions, soil fertility, management intensity, and regional agroecological characteristics [29,30,31]. For example, cereal–legume systems generally demonstrate greater nitrogen-use efficiency and productivity enhancement than cereal–cereal combinations because of complementary nutrient acquisition and biological nitrogen fixation [31,33]. Similarly, the yield advantages reported in tropical smallholder systems may differ from those observed in mechanized temperate agricultural systems owing to variations in resource availability, technological inputs, and management practices [27,29,30].

In this context, cereal–legume systems are predominant, in which cereals utilize biologically fixed nitrogen from legumes, enhancing productivity [33]. Moreover, grain–legume systems maintain soil fertility through biological nitrogen fixation and the recycling of nitrogen-rich residues, particularly in organic farming [34]. Furthermore, legume–cereal systems exhibit higher productivity than sole legume systems owing to complementary resource utilization [35]. For instance, pea (*Pisum sativum* L.) – barley (*Hordeum vulgare* L.) systems have demonstrated efficiency owing to their improved nitrogen dynamics and resource partitioning [36]. Similarly, potato (*Solanum tuberosum* L.) intercropped with dolichos (*Lablab purpureus* L.) or hairy vetch (*Vicia sativa* L.) enhances productivity, resource-use efficiency, and soil fertility in semi-humid tropics [28]. From a management perspective, large-scale farms often prefer monocropping for mechanization efficiency, whereas smallholders adopt intercropping for risk minimization, food security, and diversification purposes. Importantly, intercropping is particularly suited to organic systems because of reduced external inputs, pest and weed suppression, improved soil fertility, and resource-use efficiency [37]. However, despite the demonstrated ecological and agronomic benefits, the large-scale adoption of intercropping systems remains constrained by mechanization challenges, labor requirements, crop management complexity, and limited availability of region-specific agronomic recommendations [27,37]. Furthermore, long-term comparative studies evaluating the economic feasibility and scalability of intercropping under diverse farming systems are comparatively limited, highlighting important research gaps for future agricultural development [21,29].

5. Integration of IoT, AI, and Precision Agriculture Technologies

Over the last decade, intercropping technologies have advanced significantly, enhancing both productivity and sustainability. For instance, Si application in potato–legume systems increases productivity while reducing soil erosion in semi-humid regions [28]. Furthermore, the integration of predictive algorithms, sensor-based devices, and data-driven practices provides scalable solutions for improving agricultural productivity and sustainability [4]. In this context, smart intercropping operates through a multilayered digital architecture comprising (i) sensing, (ii) data transmission, (iii) analytics, and (iv) decision support and actuation layers. Specifically, the sensing layer employs IoT-enabled sensors to monitor soil moisture, temperature, nutrient status, and plant physiological parameters in real time. Subsequently, data streams are transmitted via wireless sensor networks (WSN) to cloud or edge platforms, where AI and ML analyze the spatial–temporal variability. Thereafter, decision support systems generate recommendations for irrigation, fertilization, and crop management, which are executed through automated or semi-automated actuation systems [38,39]. This integrated digital framework enables adaptive and data-driven farm management by facilitating continuous monitoring, predictive analytics, and precision-based resource allocation across intercropping systems [38,39].

IoT-enabled smart intercropping enhances precision agriculture outcomes by improving nutrient, water, and energy-use efficiency, thereby increasing farm profitability and sustainability.

In addition, continuous soil fertility assessment is critical for sustainable and profitable agricultural systems. Moreover, real-time sensor-based soil analysis provides insights into nutrient status, resulting in site-specific nutrient management [40]. IoT-enabled systems improve water-use efficiency by 25%–40% through real-time irrigation, while reducing input costs and resource losses [41]. Furthermore, AI-driven systems increase crop yields by 15%–25% through optimized planting, nutrient management, and pest control [41]. Additionally, integrated IoT–AI systems reduce operational costs by 20%–30% through automation and optimized resource allocation [23]. Moreover, sensor-based monitoring facilitates the early detection of crop stress and disease, reducing pesticide use by 30–50% and enhancing environmental sustainability [41]. However, the reported effectiveness of these technologies varies considerably depending on the farm scale, digital infrastructure, climatic conditions, sensor accuracy, and technological maturity [13,17,41]. For example, technologically intensive precision agriculture systems have been predominantly evaluated in large-scale or high-input agricultural systems, whereas evidence regarding their operational efficiency and economic feasibility under smallholder farming conditions remains comparatively limited [17,20]. Similarly, IoT-based irrigation systems often demonstrate greater efficiency under controlled irrigation environments than under rainfed agricultural systems, which are characterized by high climatic variability [40,41].

From a technological perspective, wireless sensor networks (WSNs), which form the backbone of IoT communication, are increasingly integrated with AI-driven precision agriculture, although challenges related to connectivity, scalability, and interoperability remain. Nevertheless, precision agriculture facilitates optimized nutrient management and targeted pesticide application, resulting in improved yields and product quality. Furthermore, remote sensing and IoT-based monitoring facilitate real-time, data-driven decision-making in agriculture [42]. Smart intercropping represents a critical convergence of ecological intensification and digital agriculture within the CSA framework. Specifically, intercropping enhances biodiversity, nutrient cycling, and resilience, whereas IoT and AI facilitate precise monitoring and adaptive management, forming a synergistic system that improves productivity and reduces environmental footprints. Nevertheless, the large-scale implementation of AI- and IoT-enabled smart intercropping systems remains constrained by high installation costs, limited digital literacy, poor Internet connectivity, interoperability limitations among digital platforms, and inadequate technical support, particularly in developing-country agricultural systems [13,17]. Furthermore, issues related to data governance, cybersecurity, maintenance requirements, and long-term economic sustainability require further investigation before widespread adoption can be achieved. Therefore, future smart intercropping systems should prioritize low-cost, scalable, and user-friendly technologies tailored to region-specific agricultural conditions and to smallholder farming systems. The quantitative benefits of integrating intercropping, climate-smart agriculture, and digital technologies, including improvements in yield, resource-use efficiency, and cost reduction, are summarized in Table 1.

Table 1. Quantitative benefits of smart intercropping and climate-smart agricultural technologies.

System/Technology	Parameter	Improvement (%)	Key Outcome	Remarks	Reference
Intercropping (cereal–legume)	Yield increase	up to 30%	Higher productivity	Higher benefits reported under diversified cereal–legume systems and favorable agroecological conditions	[29]
Intercropping (global meta-analysis)	Maize yield	4.5–8.1%	Regional yield gain	Higher yield improvements observed in Asian legume-based systems	[30]
Intercropping systems	Protein yield	36.7%	Nutritional improvement	Enhanced forage quality and nutritional output under mixed cropping systems	[31]
Intercropping systems	Nitrogen-use efficiency	40.3%	Reduced fertilizer input	Improved nutrient acquisition through biological nitrogen fixation and resource complementarity	[31]
CSA practices	Crop yield	27.5–43%	Productivity enhancement	Benefits vary according to climatic conditions, management intensity, and farming systems	[18]
CSA practices	Farm income	up to 71%	Economic benefit	Higher profitability reported under integrated climate-smart management systems	[18]

IoT-based irrigation	Water-use efficiency	25–40%	Resource optimization	Higher efficiency under controlled irrigation and sensor-based management systems	[41]
AI-based precision agriculture	Crop yield	15–25%	Decision optimization	Yield gains associated with predictive analytics and precision input management	[41]
IoT + AI integration	Cost reduction	20–30%	Economic efficiency	Automation and optimized resource allocation reduce operational expenses	[23]
Smart monitoring systems	Pesticide reduction	30–50%	Environmental sustainability	Early detection of crop stress and disease reduces excessive agrochemical application	[41]
ESA (solar irrigation)	Energy reduction	up to 60%	Energy efficiency	Renewable energy integration reduces fossil fuel dependency	[40]
Precision irrigation	Water saving	30–50%	Sustainable water use	Precision water application minimizes resource losses and pumping energy	[40]
Green AI systems	Energy efficiency	up to 86%	Reduced computational energy	Energy-efficient AI frameworks support sustainable	[43]

				digital agriculture	

6. Energy Smart Agriculture (ESA): Energy Efficiency, Carbon Reduction, and Sustainable Intensification

Energy smart agriculture (ESA) includes technologies such as zero tillage (ZT), laser land levelling, direct-seeded rice (DSR), crop residue management (CRM), legume integration (LI), precision irrigation (PWM), and site-specific nutrient management (SSNM), which collectively promote sustainable alternatives to energy-intensive conventional agriculture [20,44]. ESA optimizes energy inputs across the production cycle, including land preparation, irrigation, fertilization, and harvesting. Specifically, these systems reduce direct (fuel and electricity) and indirect (fertilizer production and agrochemicals) energy inputs through process optimization and technological substitution [45]. For instance, conservation tillage reduces fuel consumption by minimizing soil disturbance, whereas precision irrigation regulates water application based on demand, thereby reducing pumping energy. Furthermore, renewable energy integration, particularly solar-powered irrigation, replaces fossil fuel-based systems, thereby reducing energy intensity and GHG emissions [40,46]. All these interventions contribute to sustainable intensification by improving energy use efficiency while simultaneously reducing environmental footprints and production costs [19,40,44].

In this context, AI, ML, and IoT enabled systems function as integral components of smart intercropping, resulting in energy optimization through data-driven decision-making and automated control. Consequently, this framework facilitates waste minimization, cost reduction, environmental sustainability, and enhanced profitability through optimized resource allocations. Solar-powered irrigation reduces energy consumption by up to 60% compared with fossil fuel-based systems, significantly improving energy-use efficiency [40]. Moreover, the integration of renewable energy with precision agriculture reduces emissions by approximately 25% while improving productivity and resilience [40]. Additionally, precision irrigation and nutrient management reduce water use by 30%–50% and fertilizer application by 5%–15%, thereby reducing energy inputs and environmental impacts [40]. Importantly, energy-efficient AI frameworks (green AI) reduce computational energy consumption by up to 86%, emphasizing the importance of energy-aware digital agriculture [43]. However, energy-efficient technologies must be widely adopted because conventional systems are associated with higher GHG emissions and cultivation costs than conservation practices, such as ZT [19,47]. In cereal systems (wheat and rice), nitrogen fertilizers constitute a major component of energy consumption, contributing substantially to production costs and environmental impacts [19]. Globally, agriculture accounts for approximately 2.5% of the final energy consumption and approximately 30% of anthropogenic GHG emissions, underscoring the need for energy-efficient transitions [48]. Nevertheless, the effectiveness and economic feasibility of ESA technologies vary considerably across farming systems, climatic regions and socioeconomic conditions [19,40,45]. For instance, renewable energy-powered irrigation systems demonstrate greater efficiency in regions with high solar availability and irrigation infrastructure, whereas their adoption in resource-limited smallholder systems is frequently constrained by high installation costs, maintenance requirements, and limited technical expertise [40,46]. Similarly, the operational efficiency of AI- and IoT-enabled energy management systems strongly depends on digital infrastructure, connectivity, and long-term technical support [40,43,49]. Therefore, although ESA technologies substantially improve energy-use efficiency and carbon mitigation potential, their scalability remains context-dependent and requires region-specific implementation strategies to be effective.

Furthermore, ESA reduces carbon footprints while improving farmer income and is increasingly recognized in CSA frameworks [49]. Efficient management of water and energy resources is essential for sustaining the productivity of these systems. However, the large-scale adoption of digital and energy-efficient systems remains limited, indicating critical research and implementation gaps in this area. Thus, capacity building and digital training are essential for facilitating ESA adoption and improving farm productivity and income [50]. Furthermore, policy support, financial incentives, public-private partnerships, and farmer-centered technological training programs are essential for facilitating the inclusive adoption of energy-efficient agricultural technologies, particularly in developing countries [13,15,49]. Overall, ESA mitigates carbon emissions and supports sustainable agricultural intensification under climate change, while strengthening the environmental sustainability of smart intercropping systems [10]. The mechanistic components and functional interactions of smart intercropping systems integrated with CSA and digital agricultural technologies are presented in Table 2.

Table 2. Mechanistic components of smart intercropping systems integrated with CSA and digital agriculture

Component	**Mechanism**	**Technological Role**	**Outcome**
Intercropping	Niche differentiation, facilitation	Crop diversification	Yield stability
Soil processes	Biological N-fixation, rhizosphere interaction	Soil sensors, nutrient mapping	Soil fertility enhancement
Water management	Temporal complementarity	IoT irrigation systems	Water-use efficiency
Nutrient management	Resource partitioning	AI-based nutrient optimization	Reduced fertilizer input
Pest control	Biodiversity-driven suppression	AI + imaging systems	Reduced pesticide use
Energy optimization	Reduced input intensity	ESA + renewable energy	Lower carbon footprint
Decision-making	Data-driven optimization	AI/ML algorithms	Precision agriculture
Monitoring	Real-time sensing	IoT + WSN	Adaptive farm management

Source: Developed by the authors based on the literature synthesized in this study.

7. Discussion Policy Integration, Technological Advancements, and Research Directions

Global agriculture in the 21st century faces multifaceted challenges, with food insecurity and malnutrition remaining critical concerns, particularly in developing regions [2]. Approximately 20% of the global population experiences food insecurity, with high vulnerability in South Asia and Sub-Saharan Africa [51]. Therefore, addressing global hunger remains a central priority in sustainable agricultural practices. In this context, the present review demonstrates that the integration of smart intercropping with CSA and digital technologies (IoT, AI, and precision agriculture) constitutes a transformative paradigm for enhancing productivity, resource use efficiency, and climate resilience. Specifically, CSA-based systems increase rice yields from 3–4 t ha^{-1} to ~7.5 t ha^{-1} and improve water-use efficiency by 5–35%, highlighting the potential of integrated approaches [52]. Moreover, AI-driven systems facilitate real-time monitoring and predictive analytics for crop growth, soil, and climate, improving decision accuracy and input optimization [4]. Nevertheless, the effectiveness and scalability of smart intercropping systems remain highly dependent on regional agroecological conditions, farm size, technological accessibility and socioeconomic capacity [13,17,18]. Although technologically advanced agricultural systems have demonstrated substantial improvements in productivity and resource-use efficiency, the implementation of AI- and IoT-enabled agricultural technologies in smallholder farming systems remains comparatively limited [13,17,18,29,41]. Major barriers include inadequate digital infrastructure, limited Internet connectivity, insufficient technical expertise, low digital literacy, and restricted access to financial resources [13]. Furthermore, the high installation and maintenance costs associated with smart sensors, automated irrigation systems, and AI-driven decision-support platforms may disproportionately favor large-scale commercial farms, thereby widening the technological disparities within agricultural systems [13,17,53].

Furthermore, multiple sectors, including livestock, fisheries, forestry, and aquaculture, face constraints in adopting CSA owing to system complexity and resource limitations [15]. Importantly, successful implementation depends on integrating the resulting policy frameworks with technological innovations. In particular, policy support for digital infrastructure, data governance, financial incentives, and farmer training is essential. Additionally, issues of data ownership, cybersecurity, and equitable access to AI- and IoT-based tools must be addressed to ensure an inclusive transformation [53]. Thus, global initiatives should facilitate multi-stakeholder collaborations among research institutions, policymakers, and farming communities. Notably, CSA achieves its maximum impact when supported by well-defined adoption strategies, ethical implementation, and robust policy frameworks that facilitate large-scale deployments [13]. Furthermore, CSA approaches must deliver context-specific solutions supported by policies, finances, and institutional mechanisms [1]. In developing-country agricultural systems, policy interventions should particularly emphasize affordable digital technologies, open-access advisory platforms, farmer-centered training programs, and subsidy mechanisms that support smallholder adoption of climate-smart and precision agricultural technologies [13,15,20]. Moreover, interoperability among digital agricultural platforms remains an important challenge because fragmented technological systems may reduce operational efficiency, data integration capacity and scalability [38,53]. Therefore, future policy frameworks should prioritize standardized and interoperable digital agricultural infrastructure to facilitate efficient knowledge exchange and long-term technological sustainability.

7.1. Illustrative Examples from Global South and Global North Agricultural Systems

In the Global South agricultural systems, particularly in South Asia and sub-Saharan Africa, intercropping-based climate-smart agricultural practices are predominantly implemented within smallholder farming systems to improve food security, nutrient-use efficiency, and climate resilience under resource-constrained conditions. For example, cereal–legume intercropping systems in India and East Africa have demonstrated improved nitrogen-use efficiency, enhanced yield stability, and reduced dependence on synthetic fertilizers under erratic rainfall [20,28,33]. Furthermore, low-input intercropping systems integrated with organic residue recycling and precision irrigation practices have improved resource-use efficiency and livelihood resilience in smallholder communities [14,20].

Conversely, in the Global North agricultural systems, including Europe and North America, smart intercropping systems are increasingly integrated with advanced mechanization, AI-driven decision-support systems, remote sensing technologies, and automated irrigation infrastructure [17,21,29]. Large-scale European cereal–legume intercropping trials combined with precision agricultural technologies have demonstrated substantial productivity enhancement, optimized nutrient management, and reduced environmental footprints under technologically intensive farming conditions [21,29]. These contrasting examples indicate that the implementation pathways, technological complexity, and scalability of smart intercropping systems are strongly influenced by socioeconomic conditions, digital infrastructure availability, farm size, and institutional support mechanisms [13,17,21].

8. Future Perspectives

Accordingly, future research priorities include the following:

- Development of integrated intercropping–IoT–AI–CSA frameworks for real-time adaptive farm management
- Low-cost, scalable sensor technologies for smallholder accessibility
- Predictive models for climate risk assessment, yield forecasting, and pest–disease dynamics
- System-level modeling to optimize multi-cropping resource competition and facilitation

- Renewable energy (e.g., solar irrigation) integration with smart intercropping to reduce energy intensity and carbon footprint
- Socio-economic research addressing adoption barriers, including digital literacy, gender inclusion, and institutional constraints
- Standardized and interoperable digital agriculture platforms
- Long-term field-scale validation in diverse agro-climatic conditions

Future studies should prioritize long-term comparative assessments that evaluate the ecological, economic, and social sustainability of smart intercropping systems under diverse climatic and farming conditions. More evidence is required regarding the economic feasibility, operational reliability, and adoption potential of AI- and IoT-enabled agricultural systems within resource-constrained smallholder farming environments. Furthermore, integrated assessments combining productivity, environmental sustainability, energy efficiency, and socioeconomic outcomes remain limited and represent an important research gap in sustainable agricultural development [13,15,21].

A comprehensive understanding of these challenges, coupled with strategic implementation, provides a pathway toward global food security [15]. Sustainable food production requires increased investment in agricultural systems, digital infrastructure, and climate-smart technologies in agroecosystems. Ensuring food and nutritional security, aligned with Sustainable Development Goal 2 (SDG2), remains a fundamental objective of future agricultural systems [9].

9. Conclusion

The present study demonstrates that the convergence of intercropping systems with CSA and digital technologies, including IoT and AI, constitutes a transformative pathway toward sustainable and resilient food production systems. Specifically, intercropping enhances biodiversity, optimizes resource utilization, and improves soil health through biological nitrogen fixation and niche complementarity. Integration with CSA principles further improves climate resilience by reducing GHG emissions, enhancing water-use efficiency, and stabilizing crop productivity under variable environmental conditions. In this context, IoT-enabled sensing and AI-driven decision support systems facilitate real-time monitoring, predictive analytics, and precision input management. Consequently, these technologies enhance input-use efficiency, reduce operational costs, and minimize environmental impacts, thereby aligning agriculture with SI. Moreover, the ESA further strengthens this framework by optimizing energy use, promoting renewable energy, and reducing carbon footprints across the value chain. However, the effectiveness and scalability of smart intercropping systems remain highly context-dependent and are influenced by agroecological conditions, technological accessibility, infrastructure availability, farm scale, and socio-economic capacity. In particular, large-scale implementation in developing-country agricultural systems remains constrained by high investment costs, limited digital literacy, poor connectivity, interoperability, and inadequate institutional support. Therefore, future agricultural development must prioritize the integration of ecological practices with digital innovations, supported by policy frameworks, capacity building, and digital infrastructure investment. Furthermore, future research should emphasize long-term field-scale validation, region-specific technological adaptation, and integrated assessments that combine productivity, environmental sustainability, energy efficiency, and socioeconomic feasibility. Collectively, the integration of smart intercropping with CSA, ESA, and digital technologies represents a holistic framework for advancing sustainable intensification and resilient agricultural transformation. Importantly, this framework enhances productivity, resource-use efficiency, environmental sustainability, and climate resilience, thereby contributing to the global sustainable development goals.

Disclosure of Interests. The authors declare no conflicts of interest.

References

1. Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., et al.: Climate-smart agriculture for food security. Nature Climate Change **4**, 1068–1072 (2014).
2. Kakamoukas, G., Sarigiannidis, P., Maropoulos, A., Lagkas, T., Zaralis, K., Karaiskou, C.: Towards climate smart farming—A reference architecture for integrated farming systems. Telecom **2**, 52–74 (2021).
3. Yang, H., Zhang, W., Li, L.: Intercropping: Feed more people and build more sustainable agroecosystems. Engineering Agriculture **8**(3), 373–386 (2021).
4. Kumari, K., Mirzakhani Nafchi, A., Mirzaee, S., Abdalla, A.: AI-driven future farming: Achieving climate-smart and sustainable agriculture. AgriEngineering **7**, 1–30 (2025).
5. United Nations: World population prospects 2022. https://population.un.org/wpp/, last accessed 2026/03/23.
6. Lal, R.: Feeding 11 billion on 0.5 billion hectare of area under cereal crops. Food Energy Secur. **5**, 239–251 (2016).
7. Ruel-Bergeron, J.C., Stevens, G.A., Sugimoto, J.D., Roos, F.F., Ezzati, M., Black, R.E., et al.: Global update and trends of hidden hunger 1995–2011: The hidden hunger index. PLoS ONE 10, e0143497 (2015).
8. Richard, B., Qi, A., Fitt, B.D.L.: Control of crop diseases through integrated crop management to deliver climate-smart farming systems for low- and high-input crop production. Plant Pathology **71**, 187–206 (2021).
9. Sorooshian, S.: The sustainable development goals of the United Nations: A comparative midterm research review. Journal of Cleaner Production **453**, 142272 (2024).
10. Pereira, F., Caetano, N.S., Felgueiras, C.: Increasing energy efficiency with a smart farm—An economic evaluation. Energy Reports **8**, 454–461 (2022).

11. Kamboj, A., Lokesh, G., Sharma, R., Manisankar, Bhati, J., Malathi, P., Sharma, R.: Climate-smart agriculture and food security. 1st edn. Kripa Drishti Publications, Pune (2023).
12. Kumar, S., Bhatt, B.P., Dey, A., Shivani, S., Kumar, U., Idris, M., Mishra, J.S., Kumar, S.: Integrated farming system in India: Current status, scope and future prospects in changing agricultural scenario. The Indian Journal of Agricultural Sciences **88**(11), 1661–1675 (2018).
13. Gemtou, M., Isakhanyan, G., Fountas, S.: Advancing climate-smart agriculture: Integrating technology, behavioural insights and policy for a sustainable future. Smart Agricultural Technology **11**, 100861 (2025).
14. Mnukwa, M.L., Mdoda, L., Mudhara, M.: Assessing the adoption and impact of climate-smart agricultural practices on smallholder maize farmers' livelihoods in Sub-Saharan Africa: A systematic review. Frontiers in Sustainable Food Systems **9**, 1543805 (2025).
15. Matteoli, F., Schnetzer, J., Jacobs, H.: Climate-smart agriculture (CSA): An integrated approach for climate change management in the agriculture sector. In: Luetz, J.M., Ayal, D. (eds.) Handbook of Climate Change Management, pp. 1–29. Springer, Cham (2021).
16. Bedasa, Y., Gemechu, A., Bedemo, A.: Impact of combined climate-smart agriculture practices on the technical efficiency and efficiency yield gap in Ethiopia. Scientific Reports **16**, 1719 (2026).
17. Pedersen, S.M., Erekalo, K.T., Christensen, T., Denver, S., Gemtou, M., Fountas, S., Isakhanyan, G., Rosemarin, A., Ekane, N., Puggaard, L., et al.: Drivers and barriers to climate-smart agricultural practices and technologies adoption: Insights from stakeholders of five European food supply chains. Smart Agricultural Technology **8**, 100478 (2024).
18. Karakulov, F., Menglikulov, B., Mamasadikov, A., Kholbutaeva, S., Mukhtorov, A., Abdulkhaeva, G., Ruziyev, S., Durmanov, A.: The impact of climate-smart technology adoption on agricultural productivity and environmental sustainability. Emerging Science Journal **9**(6), 3087–3115 (2025).
19. Kakraliya, S.K., Jat, H.S., Singh, I., Gora, M.K., Kakraliya, M., Bijarniya, D., Sharma, P.C., Jat, M.L.: Energy and economic efficiency of climate-smart agriculture practices in a rice–wheat cropping system of India. Scientific Reports **12**, 8731 (2022).
20. Mazhar, R., Ghafoor, A., Xuehao, B., Wei, Z.: Fostering sustainable agriculture: Do institutional factors impact the adoption of multiple climate-smart agricultural practices among new entry organic farmers in Pakistan? Journal of Cleaner Production **283**, 124620 (2020).
21. Erekalo, K.T., Pedersen, S.M., Christensen, T., Denver, S., Gemtou, M., Fountas, S., Isakhanyan, G.: Review on the contribution of farming practices and technologies towards climate-smart agricultural outcomes in a European context. Smart Agricultural Technology **7**, 100413 (2024).

22. Assavarak, P., Seeprasert, P., Jirapornvaree, I.: Climate-smart integration of rice and local palm production: Enhancing resilience and sustainability in tropical agroecosystems. Research Journal of the Faculty of Social Sciences **18**(2), 26–42 (2024).
23. Rafi, M.S., Behjati, M., Rafsanjani, A.S.: Reliable and cost-efficient IoT connectivity for smart agriculture: A comparative study of LPWAN, 5G, and hybrid connectivity models. In: International Conference on Smart Computing and Informatics, pp. 389–411. Springer, Cham (2025).
24. Callaway, R.M.: Positive interactions among plants. Botanical Review **61**, 306–349 (1995).
25. Zhang, W., Zhao, Y., Li, G., Shen, L., Wei, W., Li, Z., Tuerti, T., Zhang, W.: The effects of maize–soybean and maize–peanut intercropping on the spatiotemporal distribution of soil nutrients and crop growth. Agronomy **15**(11), 2527 (2025).
26. Guerchi, A., Mnafgui, W., Garijo, G., Mahjoub, A., Ludidi, N., Gonzalez, E.M., Badri, M.: Impact of intercropping on agronomic and metabolic responses of Medicago sativa and Hordeum marinum under nutrient deficiency and drought stress. Frontiers in Agronomy **7**, 1636363 (2025).
27. Anil, L., Park, J., Phipps, R.H., Miller, F.A.: Temperate intercropping of cereals for forage: A review of the potential for growth and utilization with particular reference to the UK. Grass Forage Science **53**, 301–317 (1998).
28. Nyawade, S., Gitari, H.I., Karanja, N.N., Gachene, C.K., Schulte-Geldermann, E., Sharma, K., Parker, M.: Enhancing climate resilience of rain-fed potato through legume intercropping and silicon application. Frontiers in Sustainable Food Systems **4**, 566345 (2020).
29. Brooker, R.W., Pakeman, R.J., Adam, E., Banfield-Zanin, J.A., Bertelsen, I., Bickler, C., Fog-Petersen, J., George, D., Newton, A.C., Rubiales, D., Tavoletti, S.: Positive effects of intercrop yields in farms from across Europe depend on rainfall, crop composition, and management. Agronomy for Sustainable Development **44**(4), 35 (2024)
30. Xu, H., Hu, J., Luo, G., Wang, Y., Zhang, Y., Rong, X., Peng, J., Liao, C.: Intercropping-driven maize yield gain depending on regional environments, planting conditions, and production managements: A global-scale evidence. European Journal of Agronomy **168**, 127622 (2025).
31. Zheng, L., Li, D., Ren, H., Wang, H.: Are intercropping systems more productive than monocultures in terms of forage yield and subsequent silage quality for ruminants? A meta-analysis. Field Crops Research **332**, 110027 (2025).
32. Salari, F., Khalesro, S., Heidari, G., Zareei, S.: Competitive indices assessment in additive intercropping of borage (Borago officinalis L.) and peanut (Arachis hypogaea L.) treated with different fertilizers. Journal of crop improvement abbreviation **39**(2), 92–116 (2025).
33. Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J.B., et al.: Intercropping—a low input agricultural strategy for food and environmental security. Agronomy **11**, 343 (2021).

34. Jensen, E.S., Hauggaard-Nielsen, H.: How can increased use of biological N2 fixation in agriculture benefit the environment? Plant Soil **252**, 177–186 (2003).
35. Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S.: Interspecific competition, N use and interference with weeds in pea–barley intercropping. Field Crops Research **70**, 101–109 (2001).
36. Corre-Hellou, G., Crozat, Y.: Assessment of root system dynamics of species grown in mixtures under field conditions using herbicide injection and 15N natural abundance methods: A case study with pea, barley and mustard. Plant Soil **276**, 177–192 (2005).
37. Hauggaard-Nielsen, H., Jørnsgaard, B., Kinane, J., Jensen, E.: Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. Renewable Agriculture and Food Systems **23**, 3–12 (2008).
38. Mansoor, S., Iqbal, S., Popescu, S.M., Kim, S.L., Chung, Y.S., Baek, J.H.: Integration of smart sensors and IoT in precision agriculture: Trends, challenges and future prospectives. Frontiers in Plant Science **16**, 1587869 (2025).
39. Eyasin, M.S., Sobhani, M.E., Nasrin, S., Al Rafi, A.S., Islam, A.M.: CropSynergy: Harnessing IoT solutions for smart and efficient crop management. Crop Design, **5**(1), 100127 (2025).
40. Kumar, S.N., Suriyan, K., Jacob, A.T., et al.: Smart farming for a sustainable future: Implementing IoT-based systems in precision agriculture. Bulletin of the National Research Centre **49**, 71 (2025).
41. Shoba, H., Nagaraja, G., Krishnamma, P.N., Sreedevi, M.S.: Smart farming: Integration of IoT and AI in agricultural engineering. International Journal of Agriculture Extension and Social Development **7**(9), 692–700 (2024).
42. Aggarwal, K., Reddy, G.S., Makala, R., Srihari, T., Sharma, N., Singh, C.: Studies on energy efficient techniques for agricultural monitoring by wireless sensor networks. Computers & Electrical Engineering **113**, 109052 (2024).
43. Elbasi, E., Alzoubi, Y.I., Topcu, A.E., Nadeem, M.: Green AI for smart agriculture: Energy-efficient predictive models for crop yield and resource management. IEEE Access **13**, 204924–204953 (2025).
44. Jabbar, A., Wu, Q., Peng, J., Zhang, J., Imran, A., Yao, L.: Synergies and determinants of sustainable intensification practices in Pakistani agriculture. Land **9**(4), 110 (2020).
45. Aryal, J.P., Jat, M.L., Sapkota, T.B., Khatri-Chhetri, A., Kassie, M., Rahut, D.B., Maharjan, S.: Adoption of multiple climate-smart agricultural practices in the Gangetic plains of Bihar, India. International Journal of Climate Change Strategies and Management **10**(3), 407–427 (2018)
46. World Intellectual Property Organization: Green rural energy solutions—Clean energy solutions for agriculture (on-farm). https://www.wipo.int/web-publications/green-technology-book-expo-edition/en/3-2-green-rural-energy-solutions-clean-energy-solutions-for-agriculture-on-farm.html, last accessed 2026/03/23

47. Yuan, S., Peng, S.: Input-output energy analysis of rice production in different crop management practices in central China. Energy **141**, 1124–1132 (2017).
48. Renewable Energy Policy Network for the 21st Century: Renewables in agriculture. In: Renewables 2025 global status report. https://www.ren21.net/gsr-2025/sectors/agriculture/, last accessed 2026/03/23.
49. Sher, A., Mazhar, S., Rahut, D.B., Yuan, H.: Leveraging internet use for sustainable agriculture: The impact of digital training on adoption of energy-smart agricultural practices and welfare. Scientific Reports **15**, 30946 (2025).
50. Aijaz, U., Butt, H.D.: Poverty alleviation & CPEC: As the nexus of transformative blue economy. In: Essays on China–Pakistan Economic Corridor Beyond, p. 34 (2023).
51. Wheeler, T., von Braun, J.: Climate change impacts on global food security. Science **341**(6145), 508–513 (2013).
52. Regmi, S., Paudel, B.: Climate-smart agriculture: A review of sustainability, resilience, and food security. Archives of Agriculture and Environmental Science **9**(4), 832–839 (2024).
53. Miller, T., Mikiciuk, G., Durlik, I., Mikiciuk, M., Łobodzińska, A., Śnieg, M.: The IoT and AI in agriculture: The time is now—A systematic review of smart sensing technologies. Sensors **25**(12), 3583 (2025).