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A Bibliometric and Qualitative Review of Sustainability Dynamics in Integrated Crop – Livestock Systems

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ABSTRACT

Integrated Crop–Livestock Systems (ICLS) have emerged as important strategy for advancing sustainable agriculture by addressing productivity, environmental, and socio-economic challenges. This study examines the sustainability dynamics, emerging research trends, thematic developments, and knowledge gaps in global ICLS research. A combined bibliometric and qualitative review was conducted using Scopus-indexed publications (2015–2026) retrieved with the keyword "sustainability integrated crop–livestock." Network and overlay visualizations were employed to analyze keyword co-occurrence, thematic clusters, and research evolution. A qualitative synthesis explored food security, socio-economic impacts, environmental sustainability, and climate resilience. The results indicate a significant increase in scientific output, reflecting growing global interest in sustainability-oriented crop–livestock integration. Sustainability emerged as the central research theme linking climate change, food security, biodiversity, and agricultural productivity. ICLS enhance productivity through nutrient recycling, efficient resource utilization, and improved soil fertility, while strengthening food security through diversified production and improved nutritional outcomes. Environmental benefits include healthier soils, biodiversity conservation, reduced reliance on external inputs, and lower greenhouse gas emissions. Socio-economically, ICLS promote income diversification, employment opportunities, and livelihood resilience, particularly among smallholder farmers. Future research should prioritize context-specific implementation strategies and system optimization to maximize sustainability outcomes.

1. INTRODUCTION

Agricultural systems worldwide are increasingly required to deliver higher productivity while simultaneously addressing environmental degradation, climate variability, and socio-economic uncertainties. Conventional monoculture systems, although effective in maximizing short-term yields, often lead to soil degradation, biodiversity loss, and increased dependence on external inputs, thereby undermining long-term sustainability and resilience. In response to these challenges, Integrated Crop–Livestock Systems (ICLS) have emerged as a promising approach that reconnects crop and livestock production within a unified framework to improve system performance and sustainability outcomes [1], [2], [3]. By combining plant and animal components, ICLS create synergies that improve resource-use efficiency, strengthen ecosystem functions, and support more resilient and adaptive agricultural systems under changing environmental conditions.

At the core of ICLS is the principle of circular resource flows, where outputs from one subsystem serve as inputs for another. This integration supports efficient nutrient cycling of reusing crop residues and livestock manure, reducing reliance on synthetic fertilizers and improving soil fertility [4], [5], [6]. Empirical evidence highlights that recycling organic materials within integrated systems enhances soil structure, water retention capacity, and microbial activity, all of which contribute to improved agroecosystem functionality and resilience. Moreover, the utilization of crop residues as livestock feed and the application of manure as organic fertilizer create closed nutrient loops that minimize waste and environmental externalities while promoting sustainable intensification. These mechanisms not only support soil health but also reduce input costs, thereby strengthening both environmental and economic sustainability.

Beyond nutrient cycling, ICLS enhance ecological stability by promoting biodiversity at multiple levels, including species, genetic, and landscape diversity. Increased biodiversity in these integrated systems contributes to essential ecosystem services such as natural pest regulation, pollination, and soil fertility, which collectively enhance system resilience to environmental stresses [7], [8], [9]. Biodiversity-rich agroecosystems are better equipped to withstand climateinduced shocks, including droughts, pests, and diseases, due to their increased adaptive capacity and functional redundancy. Studies indicate that diversified agricultural systems can stabilize productivity and reduce vulnerability by providing ecological buffers against disturbances, thereby supporting long-term sustainability. In this context, genetic diversity in both crops and livestock plays a crucial role in maintaining resilience by enabling adaptation to changing environmental conditions and emerging risks.

In addition to ecological benefits, ICLS offer significant economic advantages by diversifying production outputs and reducing exposure to market and climatic risks. By integrating crop and livestock enterprises, farmers can generate multiple income streams, thereby improving financial stability and reducing dependency on single commodities. Evidence suggests that integrated systems can achieve productivity levels comparable to, or even exceeding, those of specialized systems under certain conditions, while maintaining lower environmental impacts [1], [10], [11]. Meta-analytical findings indicate that crop yields in ICLS are generally similar to those in conventional systems, with the added benefit of enhanced total system productivity due to livestock outputs. Furthermore, economic evaluations show that ICLS can provide greater economic value per hectare, lower operational risks, and improved return on investment than monoculture systems, particularly when system design and management are optimized. These attributes make ICLS a viable strategy for improving farm profitability while mitigating production risks in uncertain environments.

Despite these advantages, the performance and sustainability outcomes of ICLS are highly context-dependent, influenced by factors such as management practices, species composition, soil conditions, and institutional support. Effective implementation requires careful coordination of crop and livestock components, including appropriate stocking rates, grazing management, and crop rotations, to maximize synergies and minimize trade-offs [6], [11], [12]. Moreover, the adoption of ICLS is often constrained by limited access to knowledge, financial resources, and supportive policy frameworks often constrains ICLS adoption, particularly among smallholder farmers. Addressing these barriers is essential to unlock the full potential of integrated systems and ensure their scalability and long-term viability.

The integration of complementary approaches, such as agroforestry, regenerative agriculture, and climate-smart practices, can further enhance the sustainability and resilience of ICLS. These approaches reinforce ecosystem services, promote carbon sequestration, and improve resource-use efficiency, thereby contributing to climate change mitigation and adaptation [2], [3], [10]. For instance, incorporating trees into crop–livestock systems can improve soil structure, provide additional income sources, and enhance biodiversity, while regenerative practices emphasize soil health and ecological balance. Such integrated strategies align with broader sustainability goals and support the transition towards circular and nature-inclusive agricultural systems.

In summary, Integrated Crop–Livestock Systems represent a holistic and multifunctional approach to agricultural development that addresses the interconnected challenges of productivity, environmental sustainability, and resilience. By enhancing nutrient cycling, biodiversity conservation, and economic diversification, ICLS contribute to more sustainable and adaptive farming systems capable of responding to climate variability and market uncertainties. However, their effectiveness depends on context-specific management, supportive policies, and continuous innovation. When appropriately designed and implemented, ICLS offer a promising pathway toward resilient, productive, and biodiversity-friendly agricultural systems that align with global sustainability objectives [4], [7], [13].

This review aims to provide a comprehensive and intellectually rigorous synthesis of sustainability research in integrated crop–livestock systems (ICLS) by combining bibliometric and qualitative review approaches. Specifically, the study seeks to: (1) analyze publication trends from 2015 to 2026 to identify the growth, distribution, and developmental trajectory of sustainability research in ICLS; (2) map and interpret keyword clusters to reveal dominant research themes, intellectual structures, and emerging areas of scholarly interest; (3) examine the thematic evolution of the field to understand shifts in research priorities and conceptual frameworks over time; and (4) conduct a qualitative synthesis of the sustainability dimensions addressed in the literature, including environmental, economic, social, and climate resilience outcomes. By combining quantitative science mapping with critical descriptive analysis, this review aims to identify knowledge gaps, highlight future research directions, and deepen understanding of how integrated crop–livestock systems contribute to sustainable agricultural development, resource efficiency, food security, and adaptive capacity, particularly in developing and agrarian contexts.

2. BIBLIOMETRIC APPROACH

Data were retrieved from the Scopus database on May 25, 2026, yielding 537 publications published between 2015 and 2026. During screening, 12 duplicate records and 380 records were excluded for irrelevant topics (28 records), studies not focusing on integrated crop-livestock systems (ICLS) (152 records), or document types that did not meet the inclusion criteria (200 records). Consequently, 145 publications were retained for bibliometric analysis. From this final dataset, we identified 30 emerging keywords associated with research trends from 2024 onward, including sustainable development, regenerative agriculture, and climate-smart agriculture. These keywords highlight evolving research priorities within the discourse on ICLS sustainability and offer valuable direction for future research, as illustrated in Figure 1.

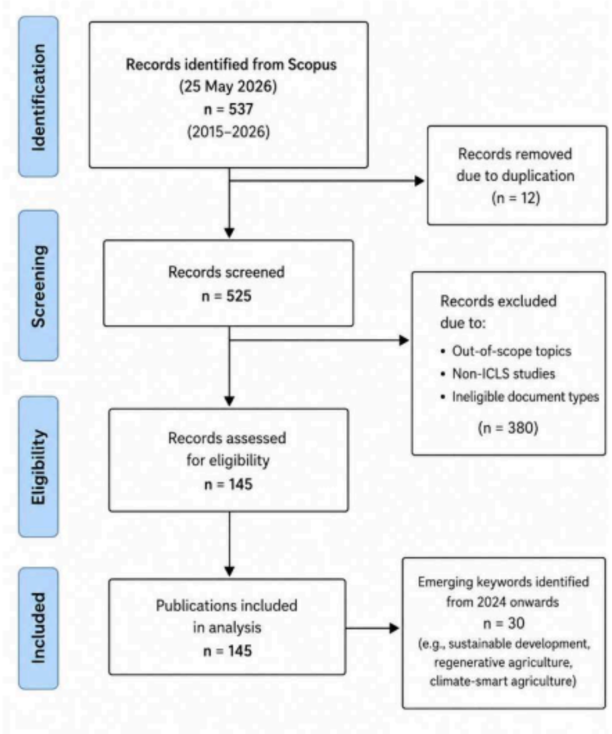

Figure 1. Prisma Diagram

A systematic literature search identified studies related to the sustainability of Integrated Crop–Livestock Systems (ICLS). The search was performed in major scientific databases such as Scopus using the Boolean search string: ("integrated crop-livestock system" OR "crop-livestock integration" OR "integrated farming system" OR "mixed crop-livestock system*" OR "crop-animal integration") AND (sustainab* OR "sustainable agriculture" OR "environmental sustainability" OR "economic sustainability" OR "social sustainability" OR resilience OR "resource efficiency" OR "circular agriculture" OR "ecosystem services")**. The inclusion criteria comprised peer-reviewed journal articles, conference papers, and review articles published in English between 2015 and 2026 that explicitly addressed integrated crop–livestock systems and examined at least one dimension of sustainability, including environmental, economic, social, or overall system sustainability. We also included studies providing empirical evidence, modeling analyses, sustainability assessments, or comprehensive reviews. Conversely, studies were excluded if they focused solely on crop production or livestock production without system integration, lacked sustainability-related outcomes, were published in languages other than English, had inaccessible full texts, or consisted of editorials, notes, letters, dissertations, and other non-peer-reviewed publications.

Figure 2 shows the documents by year in the Scopus database. The Scopus bibliometric analysis for the keyword "sustainability integrated crop–livestock" shows a clear upward trend in scientific publications over time, with a total of 537 documents recorded within the selected period (2015–2026). In the early years, publication output remained relatively low, starting with approximately 14 documents in 2015, followed by a gradual increase to around 25 documents by 2019. A notable growth phase begins in 2020, where the number of publications rises sharply to about 50 documents, indicating growing academic attention toward integrated crop–livestock systems as a sustainable agricultural model. This trend continues steadily through 2021 and 2022, maintaining around 45–50 publications per year, reflecting sustained research interest.

A significant acceleration occurs from 2023 onward, with publications rising to about 68 documents in 2023 and remaining at a similar level in 2024. The peak occurs in 2025, reaching a high of about 121 documents, highlighting a strong expansion of research activity in this field. However, in 2026, the number of documents drops to around 50 publications, likely due to incomplete indexing for the ongoing year rather than a decline in research interest. Overall, the temporal trend demonstrates that sustainability-oriented crop–livestock integration has evolved into a rapidly expanding research domain, particularly in the past five years, driven by global concerns over climate change, food security, and sustainable agricultural intensification.

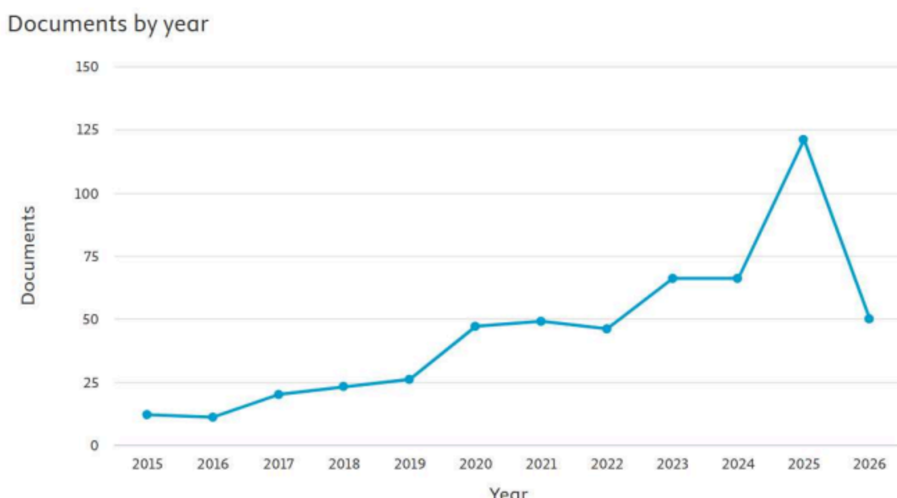

Figure 2. The documents by year in the Scopus database

Figure 3 shows the top five documents by source and year. Based on the figure 3, the Scopus search using the keyword combination "sustainability integrated crop livestock" shows that research output has been concentrated in a small number of sustainability and agriculture oriented journals, with Agricultural Systems emerging as the most influential source, contributing 26 documents, followed by Sustainability (Switzerland) with 20 documents, Science of the Total Environment with 14 documents, and Frontiers in Sustainable Food Systems with 12 documents. The annual publication trend indicates limited activity between 2015 and 2018, when most sources published fewer than two articles per year. A noticeable increase began in 2019, reflecting growing scholarly interest in integrated crop-livestock systems as a pathway to sustainable agriculture. Agricultural Systems showed intermittent but relatively high productivity, reaching publication peaks of approximately five documents in 2018, 2022, and 2026. Sustainability (Switzerland) exhibited the most consistent growth, increasing from around two publications in 2018–2019 to sustained outputs of three to four publications annually during 2020–2024, indicating its role as a major multidisciplinary platform for sustainability-related agricultural research. Science of the Total Environment demonstrated a sharp rise after 2021, peaking at about five documents in 2023, suggesting increasing attention to the environmental implications and ecosystem services of integrated crop-livestock systems. Meanwhile, Agroforestry Systems and Frontiers in Sustainable Food Systems contributed moderately but showed fluctuating publication patterns, highlighting emerging interdisciplinary links between crop-livestock integration, agroecology, and food system sustainability. Overall, the bibliometric trend suggests that research on sustainability in integrated crop-livestock systems has accelerated significantly since 2020, with publications increasingly dispersed across journals focusing on sustainable agriculture, environmental management, and resilient food production systems.

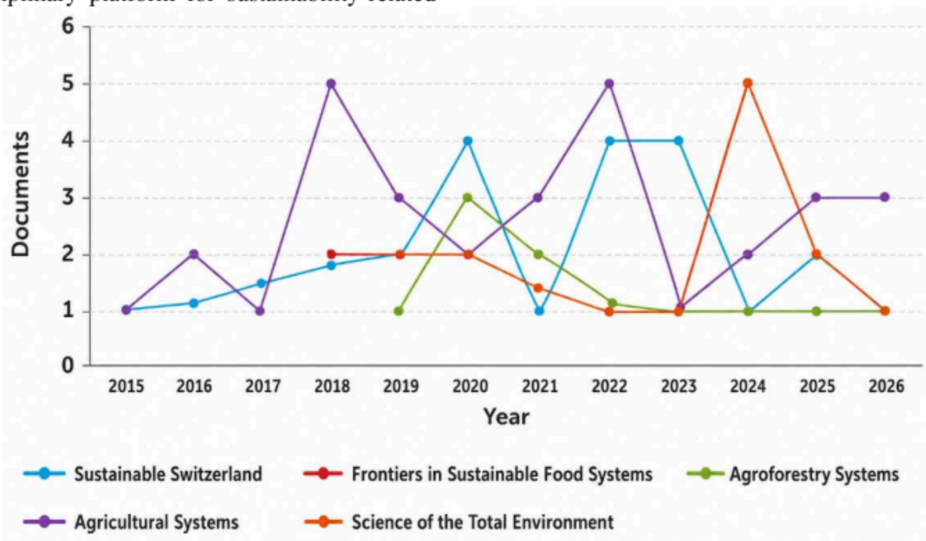

Figure 3. Top five documents by source and year.

Figure 4 shows the documents by country or territory. The bibliometric analysis of Scopus-indexed publications using the keywords "sustainability integrated crop livestock" reveals a strong geographical concentration of research output, with Brazil emerging as the leading contributor, accounting for 143 documents. This substantial lead reflects Brazil's long-standing emphasis on integrated crop-livestock (ICL) and integrated crop-livestock-forestry (ICLF) systems as sustainable land management strategies to enhance productivity while reducing environmental impacts. India and the United States rank second jointly, each contributing 97 documents, indicating significant research attention to sustainable agricultural intensification and resource-efficient farming systems in both developing and developed contexts. China follows with 51 publications, demonstrating growing interest in sustainable agricultural transitions and integrated farming approaches. European countries contribute moderately, with France (41 documents), the United Kingdom (33 documents), Italy (26 documents), Germany (23 documents), and the Netherlands (23 documents) forming a secondary cluster of research-active nations. The distribution highlights the global relevance of integrated crop-livestock sustainability research while indicating that countries with large agricultural sectors and pressing land-use challenges dominate scholarly production. Overall, the bibliometric pattern suggests that research on sustainability-oriented integrated crop-livestock systems is driven primarily by nations seeking to balance agricultural productivity, environmental conservation, climate resilience, and food security, with Brazil serving as the principal knowledge hub in this research domain.

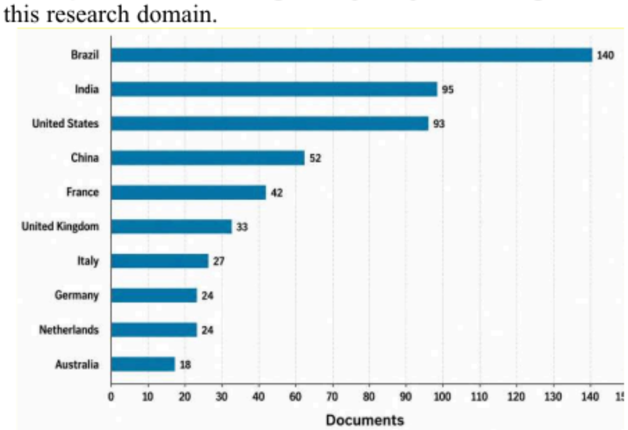

Figure 4. The documents by country or territory

The keyword co-occurrence network presented in Figure 5 was generated using VOSviewer (version 1.6.20) based on a co-occurrence analysis of keywords. The unit of analysis consisted of both author keywords and indexed keywords, enabling a comprehensive representation of the research landscape. We applied the full counting method, counting each keyword occurrence equally in the network construction. A minimum keyword occurrence threshold of 5 was established to filter and retain the most relevant terms for visualization. We normalized the network using the association strength method, VOSviewer's default normalization technique, to ensure accurate mapping of relationships among keywords. Clustering was conducted using the VOSviewer modularity-based clustering algorithm with a resolution parameter of 1.00 and a minimum cluster size of 1, resulting in the identification of distinct thematic groups within the dataset. Before analysis, a thesaurus file merged synonymous terms, standardized spelling variations, and removed non-informative keywords, improving the network's consistency and interpretability. The resulting visualization provides a comprehensive overview of the intellectual structure and thematic relationships underlying sustainability research in integrated crop–livestock systems.

Figure 5 shows the network visualization in VOSviewer. The VOSviewer network visualization shows that "sustainability" is the central and most influential keyword, with the highest level of co-occurrence and serving as a bridge across all research themes. It is strongly linked with major concepts such as climate change, food security, agriculture, and crop–livestock integration, reflecting the interdisciplinary nature of sustainability research in integrated farming systems. The prominence of nodes such as sustainable agriculture, climate change, and food security indicates that current research is heavily oriented toward addressing global challenges related to resource management, environmental degradation, and agricultural productivity. The dense interconnections among these keywords suggest that sustainability research in crop–livestock systems is not isolated but embedded within broader debates on environmental resilience and global food systems.

The cluster structure also shows the field's thematic diversity. One cluster focuses on environmental sustainability and system efficiency, including keywords such as soil quality, nutrient cycling, greenhouse gases, and sustainable intensification, highlighting efforts to improve environmental performance and reduce emissions. Another prominent cluster represents the technical implementation of crop–livestock integration, incorporating terms such as grazing, crop rotation, climate-smart agriculture, and conservation agriculture, which emphasize adaptive and resource-efficient farming practices. In parallel, a separate cluster centres on agricultural production and food systems, linking livestock, agriculture, integrated pest management, and food security, indicating the role of integrated systems in enhancing productivity and resilience under climate variability.

Additionally, the network identifies emerging and supportive research dimensions related to ecosystem services, economic viability, and system resilience. Keywords such as profitability, soil health, livelihood, and integrated farming system highlight the increasing importance of evaluating sustainability from a socio-economic perspective. Meanwhile, the presence of biodiversity, agroecology, agroforestry, and animal welfare reflects a growing shift towards holistic and regenerative approaches in agricultural systems. The relatively smaller yet distinct presence of resilience and crop–livestock nodes suggests an emerging research direction focusing on adaptation and long-term stability. Overall, the bibliometric structure confirms that sustainability-oriented crop–livestock integration research is evolving towards a comprehensive framework that simultaneously addresses environmental integrity, economic viability, and social well-being.

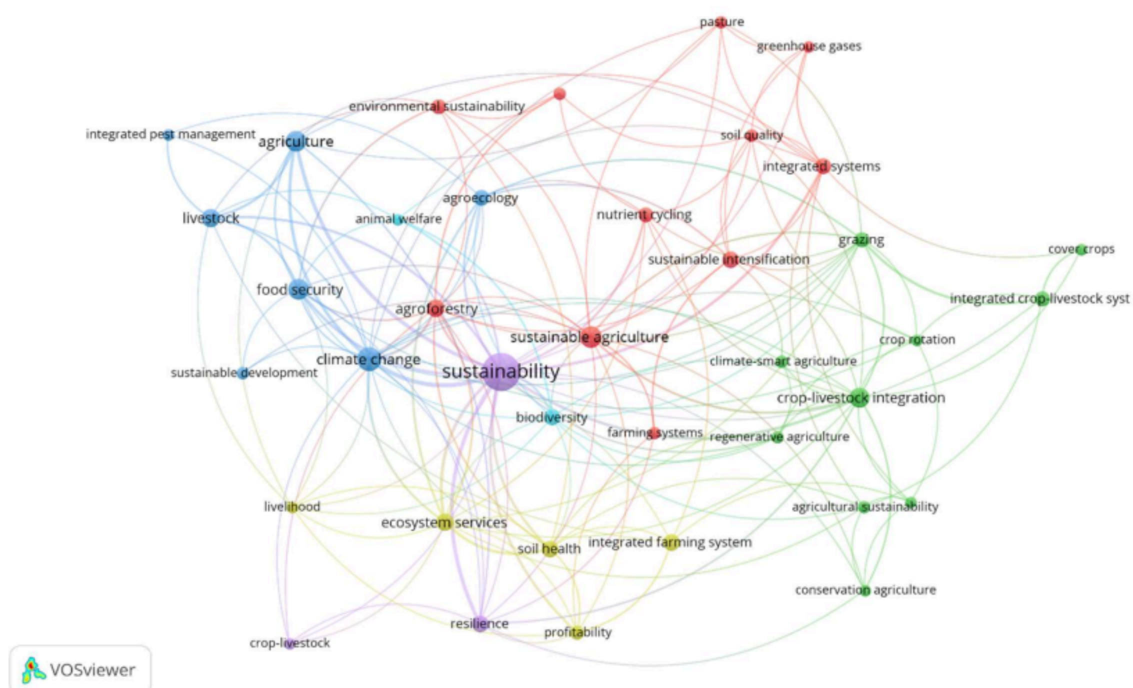

Figure 5. The network visualization in VOSviewer

Figure 6 shows the Overlay visualization in VOSviewer. The overlay visualization reveals a clear temporal progression in the research landscape of climate-smart agriculture (CSA), regenerative agriculture, and sustainable development, as indicated by the color gradient ranging from earlier studies (blue, ~2021) to more recent contributions (yellow, ~2024). Foundational themes such as crop–livestock integration, agriculture, and soil quality appear in earlier stages, reflecting the long-standing focus on system integration and productivity enhancement [14], [15]. These early clusters emphasize biophysical optimization, including nutrient cycling and soil–plant interactions, as key elements of sustainable intensification [16], [17]. In contrast, more recent keywords such as regenerative agriculture, climate-smart agriculture, and cover crops are positioned in yellow tones, indicating emerging research frontiers. This temporal shift reflects a growing focus on holistic sustainability frameworks that integrate ecological restoration, climate resilience, and socio-economic outcomes [18], [19]. The transition from productivity-centred approaches to resilience- and regeneration-oriented paradigms highlights a paradigm shift in agricultural research towards multifunctional and adaptive systems.

The keyword sustainability occupies a central and highly connected position in the network, serving as a conceptual hub linking diverse thematic domains, including food security, climate change, ecosystem services, and biodiversity. This centrality reflects the integrative nature of sustainability as a multidimensional construct encompassing environmental, economic, and social dimensions [20], [21]. Strong linkages between sustainability and food security confirm that agricultural systems are increasingly evaluated by their capacity to ensure a stable and nutritious food supply under changing climatic conditions [22], [23]. Simultaneously, connections with ecosystem services and biodiversity highlight the growing recognition of ecological functions, such as soil fertility, pest regulation, and carbon sequestration, as critical components of sustainable agriculture [24], [25]. These interconnections reinforce the argument that sustainability is not an isolated goal but a systems-based framework requiring integrated solutions across multiple scales.

The overlay analysis indicates that CSA and regenerative agriculture are among the most recent and rapidly evolving research areas. The positioning of climate-smart agriculture in proximity to sustainable intensification, nutrient cycling, and greenhouse gases suggests a strong emphasis on climate mitigation and adaptation strategies [18], [26]. CSA research increasingly integrates advanced modelling, emission reduction strategies, and adaptive management to address climate variability and environmental constraints [27], [28]. Similarly, regenerative agriculture is closely linked to keywords such as soil health, biodiversity, and conservation agriculture, reflecting its core focus on restoring ecosystem functions and enhancing resilience [19], [29]. Empirical evidence indicates that regenerative practices improve soil organic matter, increase microbial diversity, and enhance system productivity over the long term [30], [31]. The co-occurrence of CSA and regenerative agriculture suggests a convergence of these approaches as complementary strategies within sustainable development pathways.

The keyword crop–livestock integration appears as a bridging node connecting traditional agricultural practices with emerging sustainability concepts. Its strong links with grazing, soil health, biomass production, and integrated systems highlight its role in enhancing resource efficiency and circularity [18], [32]. Integrated systems help close nutrient cycles, improve soil carbon stocks, and reduce environmental impacts through synergistic interactions between crops and livestock [17], [33]. Additionally, the association with agroforestry and integrated farming systems indicates a broader shift towards multifunctional land-use strategies that combine agricultural production with ecological restoration [34], [35]. Such systems are particularly relevant in smallholder and developing contexts, where they support livelihood diversification and resilience [36], [37]. The persistence of this keyword across different temporal phases suggests its foundational role in both historical and emerging agricultural paradigms.

Another notable trend in the overlay visualization is the increasing prominence of technology-related keywords, including precision agriculture, AI, IoT, and digital agriculture. Although not all are explicitly labelled in the figure, their conceptual presence is reflected in links with productivity, monitoring, and decision-support systems. These technologies enable real-time data collection, precision input application, and improved system management, thereby enhancing efficiency and sustainability [38], [39]. For instance, AI-integrated drone systems and digital monitoring tools have been shown to improve pest management and optimize resource use in agricultural systems [38], [40]. Furthermore, innovations such as digital twins and remote sensing facilitate predictive modelling and adaptive decision-making in complex agroecosystems [41], [42]. The integration of these technologies with CSA and regenerative practices underscores the role of digital transformation in accelerating sustainable agricultural transitions.

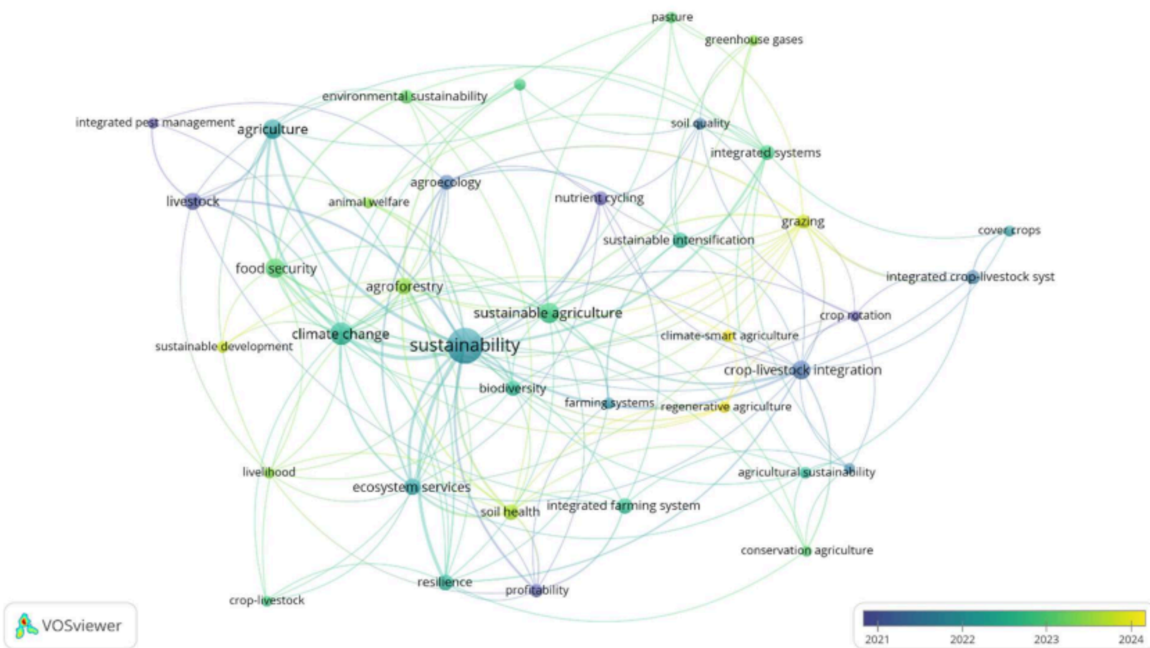

Figure 6. The Overlay visualization in VOSviewer

3. RESEARCH METHODS

This study used a narrative review and synthesis approach to examine Integrated Crop-Livestock Systems (ICLS) in enhancing agricultural productivity, food security, and sustainability. The methodology involved an extensive review of peer-reviewed literature, supported by the analysis of global case studies and empirical evidence from diverse agricultural contexts worldwide. The review evaluated the contributions of ICLS to increased food production and resource-use efficiency, nutritional improvements through enhanced dietary diversity and greater availability of animal-source foods, and crop diversification as a strategy to improve system resilience and reduce production risks. In addition, the study examined the multifunctional role of crop-livestock integration, including its implications for nutrient cycling, farm productivity, and livelihood security. The analysis also assessed the socio-economic impacts of ICLS, including income generation, employment opportunities, and risk mitigation, as well as its contributions to environmental sustainability through improved soil health, biodiversity conservation, nutrient recycling, and reduced dependence on external agricultural inputs. Finally, the review explored the role of ICLS in enhancing climate resilience by strengthening adaptive capacity, improving system flexibility, and supporting long-term agricultural sustainability under changing climatic conditions. Through this integrative synthesis, the authors developed a holistic understanding of how ICLS can address food security, environmental challenges, and rural development objectives simultaneously.

Research Methods should be explicitly positioned as a qualitative follow-up stage to the bibliometric mapping presented in Section 2. Accordingly, VOSviewer was used not only to identify publication patterns and relationships among keywords but also to provide the basis for defining the focus and structure of the narrative synthesis. The keyword clusters identified through VOSviewer, particularly themes such as sustainable development, regenerative agriculture, climate-smart agriculture, food security, resource-use efficiency, and climate resilience, were used as initial thematic codes for grouping the 145 publications into major themes. We then examined articles within each cluster in greater depth based on their research objectives, agricultural contexts, ICLS approaches, empirical findings, and contributions to productivity, food security, socioeconomic development, and environmental sustainability. Where differences or inconsistencies emerged across studies, the findings were compared by research context and methodology. They reported empirical evidence, allowing these differences to enrich rather than be excluded from the synthesis. The identified themes were subsequently validated by examining the consistency between the VOSviewer mapping results, keyword frequency and co-occurrence patterns, and the evidence reported in the reviewed articles. Through this approach, the bibliometric analysis served as an evidence-based framework for identifying and mapping research trends. At the same time, the narrative synthesis extended these findings into a deeper interpretation of the mechanisms, benefits, challenges, and future development of ICLS. The analysis focused on data from 2024 to 2026 to capture emerging and compelling research trends reflected in the VOSviewer visualizations and bibliometric analysis, enhancing the novelty and relevance of the findings.

4. CONTRIBUTIONS TO FOOD SECURITY

4.1 Increased Food Production and Efficiency

A central finding across the literature is that ICLS significantly improves farm-level productivity and resource-use efficiency. This result is primarily achieved through circular resource flows, where outputs from one subsystem are reutilized as inputs for another, thereby optimizing nutrient cycling and reducing waste [16], [32]. For instance, livestock manure is utilized as an organic fertilizer for crop production. In contrast, crop residues serve as feed resources for animals, creating a closed-loop system that enhances overall production efficiency [35]. Empirical studies show that these synergies increase yields and improve soil fertility. Integrated nutrient management approaches combining organic inputs and biological processes have been shown to improve crop productivity, forage quality, and soil health indicators [43], [44]. Similarly, crop–livestock integration has been associated with increased soil carbon and nitrogen stocks, which are critical for sustaining long-term agricultural productivity [32], [45]. These improvements are further supported by higher soil biological activity and organic matter content under integrated systems than under conventional monoculture practices [30], [31].

In addition to soil-related benefits, ICLS contributes to production efficiency through improved system-level performance. Integrated systems enable farmers to maximize output per unit area and time by combining multiple enterprises (e.g., cropping, livestock rearing, and pasture management) within a single production framework [46]. This integration reduces production risks and improves overall farm profitability, as shown in studies reporting higher yields and economic returns in integrated farming models [37]. Consequently, ICLS provides a pathway for sustainable intensification, achieving higher productivity without proportional increases in external inputs or environmental degradation [18], [20].

4.2 Nutritional Improvements, Crop Diversification and System Resilience

The results further indicate that ICLS contributes significantly to improving dietary diversity and nutritional outcomes. By producing both plant- and animal-based foods, integrated systems expand the range of available nutrients, thereby addressing multiple dimensions of food security, including availability, access, and utilization [15], [47]. Livestock components, in particular, play a critical role in supplying high-quality proteins and essential micronutrients such as iron and vitamins, which are often deficient in plant-based diets [23], [48]. Evidence from integrated farming studies shows that diversification of production systems leads to improvements in dietary diversity indicators, including food consumption scores and household dietary diversity [15], [47]. These outcomes are particularly important in smallholder farming systems, where limited access to diverse foods is a major cause of malnutrition. The integration of livestock enhances the nutritional value of diets while also providing a stable supply of animal-source foods such as milk, meat, and eggs [46], [48]. Moreover, the co-production of food and feed within ICLS enhances nutritional resilience by reducing dependence on external food markets and improving household self-sufficiency [47]. This assertion is especially relevant in regions vulnerable to food insecurity, where integrated systems can simultaneously address undernutrition and poverty through improved access to diverse and nutrient-rich foods [36], [37].

Another critical contribution of ICLS lies in its ability to promote crop diversification and enhance system resilience. Diversified cropping systems within ICLS improve agronomic performance by reducing vulnerability to pests, diseases, and climate variability [49], [50]. These systems also enhance ecosystem services such as soil fertility, water retention, and biodiversity, which are essential for maintaining stable agricultural productivity under changing environmental conditions [19], [35]. The literature highlights that diversified systems improve food security through multiple pathways. First, diversification increases total farm output by combining complementary crop species and livestock enterprises [47]. Second, it enhances dietary diversity by expanding the variety of foods produced on-farm [15]. Third, diversification serves as a risk management strategy, providing insurance against crop failure, market volatility, and extreme weather events [18], [51].

Integrated systems also show greater adaptive capacity to climate change because of their multifunctionality and resource efficiency. For example, the inclusion of livestock allows for flexible resource allocation, such as the conversion of crop residues into animal products during periods of crop failure [18]. Similarly, diversified crop rotations and intercropping systems improve resilience by stabilizing yields and reducing dependence on a single commodity [49], [50].

4.3 The Multifunctional Role and Implications

Livestock plays a pivotal and multifunctional role within ICLS, extending beyond food production to encompass economic, social, and environmental functions. As a direct source of food, livestock provides nutrient-dense products such as milk, meat, and eggs, which are essential for improving dietary quality and addressing micronutrient deficiencies [23], [48]. In addition to its nutritional contribution, livestock serves as a key economic asset for rural households. It provides income diversification, liquidity, and financial security, particularly in smallholder farming systems with limited access to formal credit [36], [37]. Livestock can be sold or traded in response to economic shocks, thereby acting as a buffer against income variability and contributing to poverty reduction [15], [47].

Livestock also supports agricultural productivity through ecosystem services such as nutrient recycling and improved soil fertility. Animal manure is a valuable organic input that improves soil structure, nutrient availability, and crop yields [17], [35]. Furthermore, livestock integration improves labor efficiency and optimizes resources by using crop by-products and marginal lands that may not be suitable for crop production [46]. From a sustainability perspective, the integration of livestock within crop systems enhances environmental performance by reducing external input requirements and promoting circular resource use [18], [52]. These synergies reinforce the role of livestock as a critical component of resilient and sustainable food systems.

Overall, the reviewed literature provides robust evidence that ICLS contributes to food security through four key pathways: (i) increased production efficiency, (ii) improved nutritional outcomes, (iii) enhanced system resilience through diversification, and (iv) the multifunctional role of livestock. These findings underscore the importance of adopting integrated approaches to agricultural development that leverage synergies between crops and livestock [15], [47], [53]. However, despite these demonstrated benefits, several challenges remain, including limited adoption due to knowledge constraints, market barriers, and institutional limitations [20], [54]. Addressing these challenges requires targeted policy interventions, capacity-building initiatives, and investment in research and extension services to facilitate the widespread implementation of ICLS. ICLS represents a comprehensive and sustainable strategy for improving food security, particularly in smallholder and resource-constrained settings. By integrating biological, economic, and social dimensions, these systems offer a viable pathway towards resilient and inclusive agricultural development.

5. SOCIO-ECONOMIC, ENVIRONMENTAL, AND CLIMATE RESILIENCE IMPACTS

5.1 Socio-Economic Impacts

The reviewed literature consistently indicates that integrated crop–livestock systems (ICLS) enhance farm profitability compared to specialized agricultural systems. This improvement is primarily attributed to the diversification of production components, which allows farmers to generate multiple revenue streams from crops, livestock, and associated by-products [15], [46], [47]. Integrated systems optimize resource utilization by linking crop and livestock enterprises, thereby reducing input costs and increasing overall economic efficiency [16], [21]. Empirical evidence suggests that ICLS contributes to more stable and resilient farm income. Diversified production systems reduce dependency on a single commodity, mitigating the adverse effects of market volatility and production risks [20], [37]. For instance, the integration of livestock with cropping systems allows farmers to offset crop losses with livestock-derived income, thereby stabilizing household earnings [47]. This diversification strategy is particularly beneficial for smallholder farmers, who are more vulnerable to economic shocks and fluctuating agricultural outputs [36]. Moreover, integrated systems enable value addition through efficient use of agricultural by-products. Crop residues serve as feed, while manure enhances soil fertility, reducing the need for costly external inputs [16], [17]. Consequently, ICLS not only improves gross returns but also enhances net profitability by lowering production costs and increasing system efficiency [46].

ICLS also plays a significant role in enhancing rural employment opportunities. The integration of multiple enterprises within a single farming system increases labor demand across different stages of production, including crop cultivation, livestock management, feed preparation, and processing activities [46], [47]. This diversification of labor tasks increases on-farm employment and reduces seasonal unemployment commonly associated with monoculture systems [37]. In addition, integrated systems support broader rural livelihoods by creating opportunities for ancillary activities such as manure management, fodder production, and small-scale agro-processing [20]. These activities not only enhance household income but also contribute to local economic development by stimulating rural value chains [47]. Furthermore, ICLS has been linked to improved livelihood resilience, as diversified income sources enable households to better cope with external shocks, including economic downturns and climate-related disruptions [51]. By providing both food and income security, integrated systems contribute to sustainable rural development and poverty alleviation [36].

An emerging theme in the literature is the role of ICLS in promoting gender inclusion and women's economic empowerment. Integrated farming systems often involve activities traditionally managed by women, such as small livestock rearing, feed preparation, and household-level processing [55]. These activities provide women with income-generating opportunities, thereby enhancing their economic participation and decision-making capacity within households [37], [55]. The increased economic involvement of women has significant implications for household welfare, particularly in relation to nutrition and food security. Studies show that when women have greater control over resources, households are more likely to prioritize food quality and nutritional diversity [36], [55]. Thus, ICLS contributes not only to economic empowerment but also to improved household nutrition and well-being.

5.2 Environmental Sustainability

The environmental benefits of ICLS are widely documented, particularly in terms of reduced reliance on external inputs and associated pollution. By recycling nutrients within the system, ICLS reduces the need for synthetic fertilizers and chemical inputs, thereby lowering the risk of soil and water contamination [17], [56], [57]. The use of livestock manure as an organic fertilizer enhances nutrient availability while minimizing nutrient losses through leaching and runoff [16], [17]. Integrated nutrient management practices further support environmental sustainability by improving fertiliser use efficiency and reducing greenhouse gas emissions associated with fertilizer production and application [56]. Additionally, the adoption of circular agricultural practices, supported by advanced technologies such as AIoT-based systems, enhances resource efficiency and reduces environmental externalities [57].

A key environmental advantage of ICLS is its positive impact on soil health and nutrient cycling. The integration of organic inputs, including manure and crop residues, increases soil organic matter, improves soil structure, and enhances microbial activity [30], [32]. These improvements contribute to better soil fertility and increased water retention capacity, which are essential for sustained agricultural productivity [29], [34]. Studies have shown that ICLS increases soil carbon and nitrogen stocks, improving soil quality and supporting long-term ecosystem sustainability [45]. Improved soil structure also facilitates root growth and nutrient uptake, leading to more efficient use of available resources [29], [43]. Furthermore, integrated systems support the development of beneficial soil microbiomes, which play a crucial role in nutrient cycling, disease suppression, and overall ecosystem functioning [58]. Together, these processes enhance the ecological stability and productivity of agricultural systems.

ICLS contributes significantly to biodiversity conservation and the provision of ecosystem services. The diversification of crops, livestock, and associated vegetation creates heterogeneous landscapes that support a wide range of plant and animal species [24], [25]. This increased biodiversity enhances ecosystem resilience and improves the provision of services such as pollination, pest control, and soil fertility maintenance [19], [35]. Integrated systems also promote agroecological practices, including crop rotations, intercropping, and agroforestry, which further enhance biodiversity and ecosystem functionality [35], [49]. These practices reduce reliance on chemical inputs and support sustainable land management. Moreover, the integration of multiple components within ICLS facilitates the efficient use of natural resources, including water and nutrients, thereby supporting ecosystem sustainability [35], [57]. The multifunctionality of integrated systems ensures that agricultural production is aligned with environmental conservation objectives.

The literature highlights the role of ICLS in mitigating greenhouse gas (GHG) emissions through improved resource efficiency and carbon sequestration. Integrated systems reduce emissions associated with synthetic fertilizer production and use by recycling organic nutrients within the system [17], [56]. In addition, ICLS enhances carbon sequestration through increased soil organic matter and biomass accumulation, contributing to climate change mitigation [28], [45]. Studies comparing integrated and conventional systems indicate that integrated approaches can achieve lower carbon footprints while maintaining or improving productivity [52], [59]. Furthermore, the adoption of low-carbon livestock strategies within integrated systems reduces methane emissions and improves overall environmental efficiency [18], [52]. These findings underscore the potential of ICLS as a key strategy for achieving climate-smart agriculture and contributing to global mitigation efforts.

5.3 Climate Resilience

ICLS significantly enhances climate resilience by promoting diversification across crop and livestock components. This diversification reduces the vulnerability of farming systems to climate variability and extreme weather events by spreading risk across multiple enterprises [15], [20]. For example, crop failures due to drought or pests can be partially offset by livestock production, thereby ensuring continued income and food supply [20]. Diversified systems also improve adaptive capacity by enabling farmers to adjust production strategies in response to changing climatic conditions [49], [50]. This flexibility is critical for maintaining productivity under increasingly unpredictable environmental conditions.

The integration of crops and livestock enhances resource efficiency, particularly in relation to nutrient and water management. Improved soil structure and organic matter content increase soil water retention capacity, thereby reducing the impact of drought and improving crop performance under water-limited conditions [34]. In addition, nutrient recycling within ICLS supports more efficient use of available resources, reducing dependency on external inputs and enhancing system sustainability under resource constraints [16]. These characteristics contribute to the resilience of agricultural systems in the face of climate change.

Compared to specialized systems, ICLS demonstrates greater resilience to climate shocks due to its multifunctional and integrated nature. The combination of crops and livestock provides multiple buffering mechanisms, including diversified income sources, flexible resource allocation, and enhanced ecosystem services [18], [20]. Studies show that integrated systems better withstand and recover from extreme weather events, such as droughts and floods, due to improved soil health, biodiversity, and resource-use efficiency [20]. Furthermore, the inclusion of livestock allows for the utilization of crop residues during periods of crop failure, thereby maintaining productivity and food availability [15], [47]. Overall, the evidence indicates that ICLS offers a comprehensive approach to building climate-resilient agricultural systems. By integrating ecological, economic, and social dimensions, these systems provide a robust framework for addressing climate-change challenges while supporting sustainable food production.

6. LIMITATIONS AND BOUNDARY CONDITIONS

The benefits of ICLS for food security are context-dependent and may vary according to climate, farm size, land availability, labour, market access, and policy support. In land-scarce settings, competition among food crops, livestock feed, and grazing areas may limit integration, necessitating greater reliance on crop residues, marginal land, or seasonal integration. Potential trade-offs include competition between livestock and food/feed crops, zoonotic disease risks, and water pollution resulting from poorly managed manure. Therefore, improvements in productivity, nutrition, and resilience should not be assumed to apply universally across all farming systems. The evidence is further constrained by methodological limitations, including small sample sizes, short-duration trials, site-specific designs, and heterogeneous indicators and ICLS configurations. These factors limit assessment of long-term effects and reduce the generalizability of findings across different regions and farm scales. Thus, interpret the reported benefits cautiously, particularly when extrapolating results from experimental or favorable conditions to resource-constrained settings.

The socio-economic, environmental, and climate benefits of ICLS depend on appropriate management practices and local conditions. Economic performance may be constrained by labor requirements, market volatility, input costs, and inadequate infrastructure. At the same time, environmental benefits can be offset by excessive manure application, nutrient runoff, water pollution, methane emissions, or high livestock pressure. Similarly, climate-resilience benefits may vary across regions depending on factors such as climate, soil quality, water availability, farm size, and exposure to climate hazards. The reviewed studies also vary considerably in sample size, duration, location, system design, and measurement approaches, limiting direct comparison and broad generalization. Short-term and site-specific studies may not adequately capture long-term soil health, economic viability, environmental impact, and resilience outcomes. Consequently, ICLS should be considered a context-specific strategy, and its benefits should be assessed through longer-term, multi-site research that considers both synergies and potential trade-offs.

7. CONCLUSIONS

This study provides a comprehensive synthesis of the sustainability dynamics of Integrated Crop–Livestock Systems (ICLS) through a combined bibliometric and qualitative analysis. The findings clearly demonstrate that ICLS represents a rapidly expanding research domain, with a significant increase in global scientific output over the past decade, particularly since 2020. Bibliometric mapping confirms that sustainability functions as a central and integrative concept, linking key themes such as climate change, food security, biodiversity, and agricultural productivity. The emergence of research frontiers, particularly climate-smart agriculture, regenerative practices, and digital innovation, indicates a clear transition from productivity-oriented paradigms toward more holistic, resilience-driven agricultural systems.

From a systems perspective, the study highlights that ICLS significantly enhances agricultural sustainability through synergistic interactions between crop and livestock components. The integration of these subsystems improves resource-use efficiency by enabling circular nutrient flows, increasing soil fertility, and reducing dependence on synthetic inputs. These processes contribute not only to higher production efficiency and stable yields but also to improved environmental performance, including reduced greenhouse gas emissions and enhanced carbon sequestration. In addition, ICLS supports biodiversity conservation and ecosystem services, thereby strengthening ecological resilience and long-term system stability.

The study further reveals that ICLS plays a crucial role in advancing food security through multiple pathways. By combining crop and livestock production, these integrated systems increase overall food output, diversify dietary sources, and improve nutritional quality, including animal-based foods rich in essential micronutrients. Moreover, production diversification enhances system resilience by reducing vulnerability to climate variability, pests, and market fluctuations. The multifunctional role of livestock as a source of food, income, and organic inputs further reinforces ICLS's capacity to support sustainable and resilient food systems, especially in smallholder and resource-constrained contexts.

Beyond environmental and food system benefits, the socio-economic analysis underscores the importance of ICLS in improving rural livelihoods. Integrated systems contribute to higher and more stable farm incomes through diversification and input optimization, while also generating employment opportunities and supporting local value chains. Importantly, the inclusion of livestock and household-based activities promotes gender inclusion and enhances women's participation in agricultural economies. These findings highlight the broader developmental implications of ICLS for poverty reduction, livelihood resilience, and inclusive rural growth.

In terms of scientific contribution, this study advances the existing body of knowledge by integrating bibliometric evidence with a multidimensional evaluation of sustainability outcomes. It provides a structured understanding of the evolution of research on ICLS, identifies key thematic clusters and emerging trends, and situates integrated systems within the broader discourse on sustainable and climate-resilient agriculture. By bridging quantitative mapping with qualitative synthesis, the study offers a comprehensive framework for analyzing the role of ICLS in addressing global challenges related to food security, environmental degradation, and socio-economic development.

Despite these contributions, several gaps remain that warrant further investigation. Future research should focus on context-specific performance assessments of ICLS across different agroecological and socio-economic conditions, particularly in developing regions such as Indonesia and other tropical systems. In addition, more integrated modelling approaches, such as life cycle assessment, system dynamics, and techno-economic analysis, are needed to quantify trade-offs and optimize system design. The role of emerging technologies, including digital agriculture, artificial intelligence, and precision farming, also requires deeper exploration in enhancing the efficiency and scalability of ICLS. Furthermore, policy-oriented research is essential to identify institutional barriers and develop supportive frameworks that facilitate adoption among smallholder farmers.

8. DECLARATION OF AI USE

AI tools were used solely for language polishing, grammar correction, and improving readability. All data, analysis, interpretations, and conclusions are original work of the authors, who take full responsibility for the final content.

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