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Research Trends, Collaboration Networks and Emerging Themes of IoT in Agriculture: A Bibliometric Analysis in Southeast Asia

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Abstract

The increasing integration of digital technologies in agriculture has positioned the Internet of Things (IoT) as a critical enabler of smart and sustainable farming systems; however, despite the rapid expansion of research in this domain, a comprehensive understanding of its development, particularly within Southeast Asia, remains limited. This study addresses this gap by conducting a bibliometric analysis of IoT applications in agriculture, focusing on research trends, collaboration networks and thematic evolution. Bibliographic data was retrieved from the Scopus database and analyzed using performance analysis and science mapping techniques through VOSviewer and the Bibliometrix package in R. The results reveal a significant increase in scientific production, particularly after 2018, indicating the transition of the field into a rapidly expanding research domain, while the citation patterns suggest a gradual stabilization of the impact of the research, reflecting its maturation. India, Malaysia and China emerge as the leading contributors in terms of productivity, influence on citations and collaboration, although disparities in research capacity persist within Southeast Asia. Collaboration analysis highlights strong global integration but limited intra-regional connectivity, pointing to opportunities for strengthening regional research networks. Thematic analysis identifies four major research domains: IoT infrastructure, intelligent systems, sustainability and emerging digital technologies with a clear shift toward data-driven and sustainability-oriented applications. This study provides a region-specific analysis of IoT-driven agricultural research, offering insights to strengthen collaboration, research capacity and sustainable agricultural innovation in Southeast Asia and other developing regions.

Keywords: Bibliometric analysis, Internet of Things (IoT), Precision Agriculture, Smart Agriculture, Southeast Asia.

Introduction

The rapid advancement of digital technologies has significantly reshaped traditional agricultural systems, ushering in the era of smart and data-driven farming. Among these innovations, the Internet of Things (IoT) has emerged as a transformative enabler, facilitating real-time data collection, monitoring and automation across agricultural processes. IoT applications in agriculture encompass a wide range of functions, including soil moisture sensing, precision irrigation, crop health monitoring and livestock tracking, all of which contribute to improved productivity and resource efficiency. Recent studies highlight that IoT integration enhances decision-making capabilities and supports sustainable agricultural practices by optimizing inputs such as water, fertilizers and energy (1, 2). The concept of smart agriculture, often framed within Agriculture 4.0, integrates IoT with complementary technologies such as artificial intelligence, cloud computing and big data analytics to enable intelligent farm management systems. This convergence allows for predictive analytics, automation and real-time responsiveness to environmental conditions. Recent literature emphasizes that these technologies are pivotal in addressing global challenges such as food security, climate change and labor shortages (3-5). Furthermore, IoT-driven agricultural systems have been shown to significantly enhance operational efficiency while reducing environmental impact, thereby aligning with global sustainability goals. Despite the global growth of IoT-enabled agricultural research,

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regional disparities remain evident, particularly in Southeast Asia. This region is characterized by its agricultural diversity, its dependence on smallholder agriculture systems and its increased exposure to climate-related risks. While Southeast Asia holds substantial potential for digital agricultural transformation, the adoption and research development of IoT technologies remain uneven across countries due to infrastructural, economic and policy-related constraints (6-8). Emerging studies indicate that although countries such as Malaysia, Thailand and Vietnam are making progress in digital agriculture initiatives, others are still in early adoption stages, highlighting the need for a more comprehensive understanding of the region's research landscape.

In this context, bibliometric analysis has gained prominence as a robust methodological approach for systematically evaluating scientific output and mapping knowledge structures within a research domain. By analyzing large-scale bibliographic data, bibliometric techniques enable the identification of research trends, collaboration networks and thematic developments (9, 10). Recent methodological advancements have further strengthened the application of bibliometrics in interdisciplinary fields, supported by tools such as VOSviewer and Bibliometrix, which facilitate sophisticated analyses including co-authorship mapping, co-citation networks and keyword co-occurrence clustering (11, 12).

Building on this methodological foundation, bibliometric analysis provides a systematic and evidence-based approach for examining how research on IoT in agriculture has developed over time in Southeast Asia. It enables the identification of key intellectual structures, influential authors and evolving collaboration patterns that shape the field. Prior studies have shown that the integration of IoT into agriculture has expanded significantly since the mid-2010s, largely driven by advancements in low-cost sensing technologies, wireless communication systems and data-driven agricultural decision-making tools (13, 14). In this context, mapping co-authorship and institutional collaboration networks is particularly valuable, as it reveals how knowledge is produced and shared across national boundaries. This is especially relevant in Southeast Asia, where disparities in research capacity and digital infrastructure influence the pace and direction of scientific development. Global evidence also suggests that countries with stronger technological ecosystems and research funding structures tend to occupy central positions in collaboration and citation networks, thereby shaping dominant research agendas in smart agriculture (15, 16). Citation-based analyses further help trace the intellectual foundations of the field, highlighting how core themes such as precision agriculture, sensor-based monitoring and decision-support systems have gradually become established research pillars.

In addition, keyword co-occurrence and thematic evolution analysis provide deeper insights into how research priorities are shifting within IoT-enabled agriculture. Recent studies indicate a clear transition from isolated IoT applications toward more integrated and intelligent farming systems that combine artificial intelligence, cloud computing and edge analytics for real-time agricultural decision-making (14, 17). These issues are especially critical in Southeast Asia, where agriculture remains highly fragmented and resource-constrained. Although bibliometric studies on IoT in agriculture have increased in recent years, most of these analyses adopt a global perspective or focus on technologically advanced regions, thereby overlooking the unique dynamics of Southeast Asia. This limitation restricts a deeper understanding of region-specific research trends, collaboration structures and thematic priorities that are essential for guiding innovation and policy development. Moreover, existing studies often emphasize descriptive outputs without sufficiently examining the intellectual and social structure of the field. Given the strategic importance of Southeast Asia in global agricultural production and its accelerating interest in digital transformation, there remains a critical need for a focused and analytically robust bibliometric investigation.

To address this gap, the present study provides a comprehensive bibliometric analysis of IoT applications in agriculture within Southeast Asia. Specifically, it aims to

(a) analyze publication trends and growth patterns,
(b) identify key contributors including authors, institutions and countries,
(c) examine collaboration networks and
(d) uncover emerging themes and knowledge clusters.

By integrating performance analysis, collaboration network mapping, thematic evolution assessment and lifecycle modeling within a single bibliometric framework, this study extends beyond conventional publication and citation analyses commonly reported in previous research. The study's novelty lies in its region-specific focus on Southeast Asia and its comprehensive examination of the intellectual, social and developmental structure of IoT-enabled agricultural research, thereby providing insights that are not readily captured through existing global-level bibliometric investigations.

Methodology

Research Design

This study employs a quantitative bibliometric research design to systematically examine the scientific landscape of IoT applications in agriculture within Southeast Asia. Bibliometric analysis is widely recognized as a robust and reproducible approach for evaluating large volumes of scholarly data, enabling the identification of research trends, intellectual structures and collaboration patterns within a given domain. By integrating performance analysis with science mapping techniques, this study aims to provide a comprehensive and multi-dimensional understanding of the evolution and knowledge structure of IoT-driven agricultural research (18, 19).

Data Source and Search Strategy

The bibliographic data utilized in this study were retrieved from the Scopus database, which is widely recognized as one of the most comprehensive and reliable sources for bibliometric research due to its extensive coverage of peer-reviewed literature, multidisciplinary scope and standardized indexing system (20). Scopus has been extensively employed in bibliometric and scientometric investigations because it provides high-quality metadata, citation information and compatibility with leading bibliometric analysis tools such as Bibliometrix and VOSviewer. The use of a single, well-established database also enhances the consistency, transparency and reproducibility of the research process.

A structured search strategy was developed to identify publications related to the application of the IoT in agriculture within the Southeast Asian context. The search was conducted using the TITLE-ABS-KEY field to ensure that retrieved records were directly relevant to the study objectives. The search query combined keywords associated with IoT-enabled agricultural technologies and smart farming practices with geographical identifiers representing Southeast Asian countries. The final search string was defined as follows: (TITLE-ABS-KEY(("internet of things" OR IoT OR "smart agriculture" OR "precision agriculture" OR "digital agriculture" OR "agriculture 4.0")) AND (agriculture OR farming OR "crop production" OR livestock OR aquaculture) AND ("Southeast Asia" OR "South East Asia" OR Indonesia OR Malaysia OR Philippines OR Thailand OR Vietnam OR "Viet Nam" OR Singapore OR Cambodia OR Laos OR Myanmar OR Brunei)). The search was performed in March 2026 and covered publications indexed from 2000 to 2026. The starting year was selected because the early 2000s represent the formative period of IoT-related technological development and digital transformation initiatives that later influenced agricultural applications. Although the term “Internet of Things” gained broader academic recognition after 2008, extending the search period to 2000 ensured comprehensive coverage of foundational studies and early technological developments that contributed to the emergence of IoT-enabled agriculture. The inclusion of records up to 2026 allowed the analysis to capture the most recent developments and emerging research trends in the field.

To ensure the quality, consistency and scholarly relevance of the bibliometric dataset, only articles, review papers, conference papers and book chapters were retained for analysis. These document types represent primary scholarly contributions and constitute the dominant channels through which knowledge is disseminated in the fields of information technology, engineering and agricultural sciences. In contrast, editorials, notes, letters, errata, conference reviews, retracted publications and other non-research document types were excluded because they typically do not report original research findings and may introduce bias into publication, citation and collaboration analyses. Furthermore, only documents published in the English language were included to ensure consistency in data processing, thematic interpretation and bibliometric mapping. Following the application of the search criteria and data-cleaning procedures, the resulting dataset served as the basis for subsequent performance analysis, collaboration network assessment, conceptual structure mapping and lifecycle modeling.

Data Screening and Eligibility Criteria

Following data retrieval, a systematic screening process was undertaken to ensure the relevance, consistency and quality of the bibliometric dataset. The procedure adhered to established bibliometric research practices emphasizing transparency and reproducibility (21, 22). All records retrieved from Scopus were exported in CSV and BibTeX formats, including comprehensive bibliographic information such as authors, titles, abstracts, keywords, affiliations, source titles, citation data and references. The initial search yielded 10,148 records, which subsequently underwent a series of screening and eligibility procedures. Duplicate entries and incomplete records were identified and removed, followed by a relevance assessment based on titles, abstracts and author keywords. Publications that primarily addressed non-agricultural domains, including healthcare IoT, industrial IoT, smart cities, transportation systems and other unrelated applications, were excluded to ensure alignment with the study objectives and scope.

To enhance the scholarly rigor and comparability of the dataset, explicit inclusion and exclusion criteria were applied. Only articles, review papers, conference papers and book chapters were retained because these document types represent substantive scholarly contributions and constitute the primary channels of scientific knowledge dissemination within the fields of agriculture, engineering and information technology. Conversely, editorials, notes, letters, errata, conference reviews, retracted publications and other non-research document types were excluded, as they generally do not present original research findings and may introduce bias into publication, citation and collaboration analyses. Furthermore, only English-language publications were considered to ensure consistency in data processing and thematic interpretation. After applying all screening, eligibility and quality-control procedures, a final dataset of 9,788 publications was retained and subsequently used for performance analysis, collaboration network analysis, thematic mapping and lifecycle modeling.

Data Analysis Tools and Procedures

The bibliometric analysis was performed using Bibliometrix version 4.3.0 implemented through RStudio version 2024.12.1 (Posit Software, PBC, Boston, MA, USA) and VOSviewer version 1.6.20 (Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands). These software packages were selected because of their extensive application in bibliometric and scientometric research and their complementary capabilities for performance analysis and science mapping.

Initially, the cleaned Scopus dataset was imported into Bibliometrix, where descriptive and advanced bibliometric analyses were performed, including annual scientific production, publication growth trends, source analysis, citation analysis, author productivity, institutional contributions, country-level performance, thematic evolution and conceptual structure mapping. Bibliometrix was also employed to generate performance indicators and science mapping outputs that facilitated the identification of influential publications, authors and research themes. Subsequently, VOSviewer was utilized to construct and visualize bibliometric networks, including co-authorship, country collaboration, co-citation and keyword co-occurrence networks. The software employs a visualization of similarities (VOS) mapping technique that enables the detection of clusters, relational strengths and intellectual structures within a research domain (23, 24). To further examine the developmental trajectory of the field, publication growth data were exported and subjected to lifecycle trend analysis, enabling the assessment of the maturity and evolution of IoT-related agricultural research. The combined use of Bibliometrix and VOSviewer provided methodological triangulation by integrating quantitative performance analysis with network-based science mapping, thereby enhancing the robustness, reliability, transparency and reproducibility of the study's findings (25).

Bibliometric Analysis Techniques

To achieve the objectives of this study, several bibliometric techniques were applied. Performance analysis was conducted to evaluate the productivity and impact of research outputs, focusing on publication trends, citation patterns and leading contributors. This provides a quantitative overview of the development of IoT-related agricultural research in Southeast Asia (26-28). Collaboration network analysis was performed using co-authorship data to examine the relationships among authors, institutions and countries. This analysis reveals the social structure of scientific collaboration and identifies key research hubs and partnerships within the region. Furthermore, keyword co-occurrence analysis was employed to identify major research themes and emerging topics. By analyzing the frequency and co-occurrence of keywords, thematic clusters were generated to represent the conceptual structure of the field. In addition, thematic evolution analysis was conducted to track changes in research focus over time, providing insights into the dynamic development of IoT applications in agriculture (27, 29). Finally, science mapping techniques, including co-citation analysis, were applied to uncover the intellectual structure of the field by identifying influential publications and knowledge bases. These combined approaches provide a comprehensive understanding of both the conceptual and intellectual dimensions of the research domain (30).

Reliability and Reproducibility

To ensure the reliability and reproducibility of the study, several methodological considerations were implemented. The use of the Scopus database guarantees high-quality and standardized bibliographic data. The search strategy was carefully designed to balance comprehensiveness and precision, minimizing the risk of missing relevant studies while avoiding irrelevant records. Additionally, the integration of multiple bibliometric tools enhances analytical rigor through cross-validation of results. The transparent documentation of data collection, screening and analysis procedures further ensures that the study can be replicated by other researchers, which is a critical requirement for bibliometric research (31-33).

Results and Discussion

Scientific Production and Citation Impact

The annual scientific production of studies on IoT applications in agriculture demonstrates a clear and sustained upward trajectory, particularly after 2018, as illustrated in Figure 1. This growth reflects the increasing global emphasis on digital transformation in agriculture, where technologies such as IoT, artificial intelligence (AI) and data analytics are being integrated to improve productivity and sustainability. Similar trends have been reported in recent bibliometric studies, which highlight a rapid increase in publications driven by the need to address global challenges such as food security, climate change and resource efficiency.

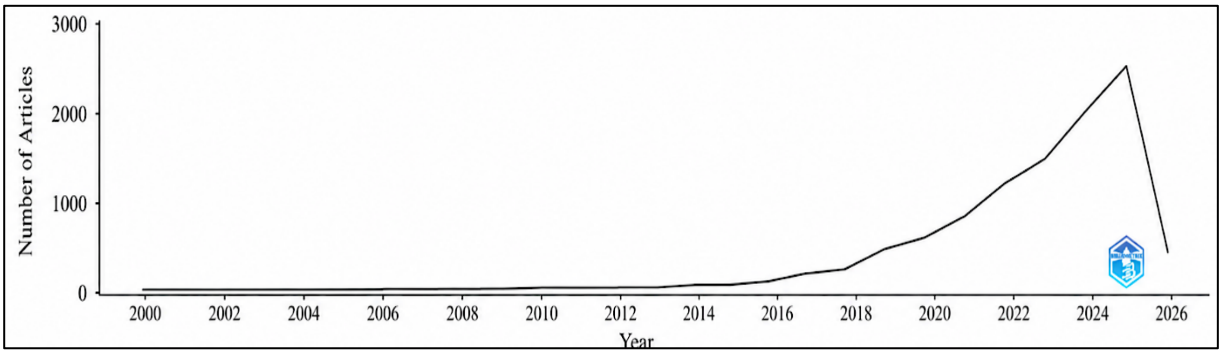

Figure 1: Annual Scientific Production of Iot Applications in Agriculture in Southeast Asia

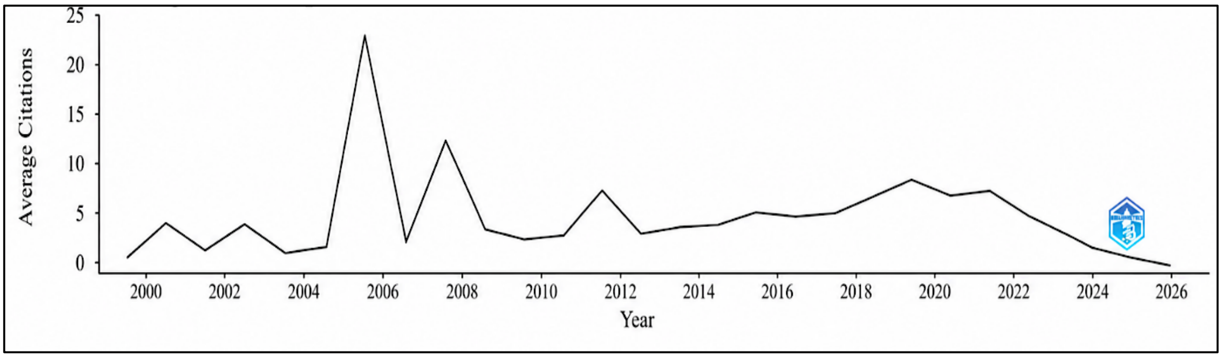

Figure 2: Average Citations Per Year of Iot Applications in Agriculture in Southeast Asia

The sharp acceleration in publication output after 2019, evident in Figure 1, suggests that the field has transitioned from an emerging domain into a rapidly expanding research area. This phase coincides with advances in sensor technologies, cloud computing and precision agriculture systems, which have enabled real-time monitoring and data-driven decision-making in agricultural practices (34, 35). In contrast, the average citation trend, shown in Figure 2, reveals a more fluctuating pattern, particularly during the early years of the study period. The highest citation counts can be attributed to foundational studies that established the theoretical and technological foundations of IoT applications in agriculture and subsequently influenced later research directions. As the volume of publications increased, citation values became more stabilized, indicating a transition from a field dominated by a few highly influential works to a broader and more diversified knowledge base. Figure 2 further demonstrates the progressive maturation of the research domain, where scholarly influence is distributed across a larger body of literature rather than concentrated in a limited number of seminal publications. This stabilization of citation performance suggests the emergence of a well-established and continuously expanding research community. The relatively lower citation values observed in recent years should be interpreted cautiously due to the time-lag effect, whereby recently published studies have had limited time to accumulate citations. In general, the combined analysis of production and citation trends in Figures 1 and 2 suggests that IoT-based agricultural research is entering a mature and dynamic phase characterized by sustained publication growth, expanding intellectual influence, and increasing scholarly engagement.

Country-level Performance, Collaboration and Research Leadership

The country-level analysis reveals a highly interconnected yet structurally uneven research landscape in IoT applications in agriculture. As shown in Figure 3, the collaboration network density indicates a moderately cohesive system, suggesting that while international research linkages are present, they are not uniformly distributed across countries. The visualization further reveals that research collaboration is concentrated around a limited number of highly connected countries, whereas several nations maintain relatively weak collaborative ties and occupy peripheral positions within the network. Such disparities may reflect differences in research capacity, funding availability, technological infrastructure, and access to international scientific partnerships. Consequently, knowledge production and dissemination within the field are influenced by a relatively small group of countries that function as major collaboration hubs. Such uneven collaboration patterns are characteristic of scientific networks, where a limited number of countries dominate knowledge production and exchange (36, 37). The structural configuration of these interactions is further illustrated in Figure 4, which reveals distinct clusters of collaboration among countries engaged in IoT-based agricultural research. A central cluster is formed around India and Malaysia, characterized by strong link strengths and dense interconnections. The prominence of these nodes indicates their role as key coordinators of research activity, facilitating collaboration both within and beyond the region. Countries occupying peripheral positions exhibit fewer collaborative links, suggesting lower levels of participation in international research networks. The clustering pattern further indicates that scientific collaboration tends to develop around established research leaders, creating interconnected knowledge hubs that influence the direction and dissemination of research within the field. In contrast, several countries remain weakly connected, reinforcing the presence of a core–periphery network structure commonly observed in global scientific collaboration networks (38-40).

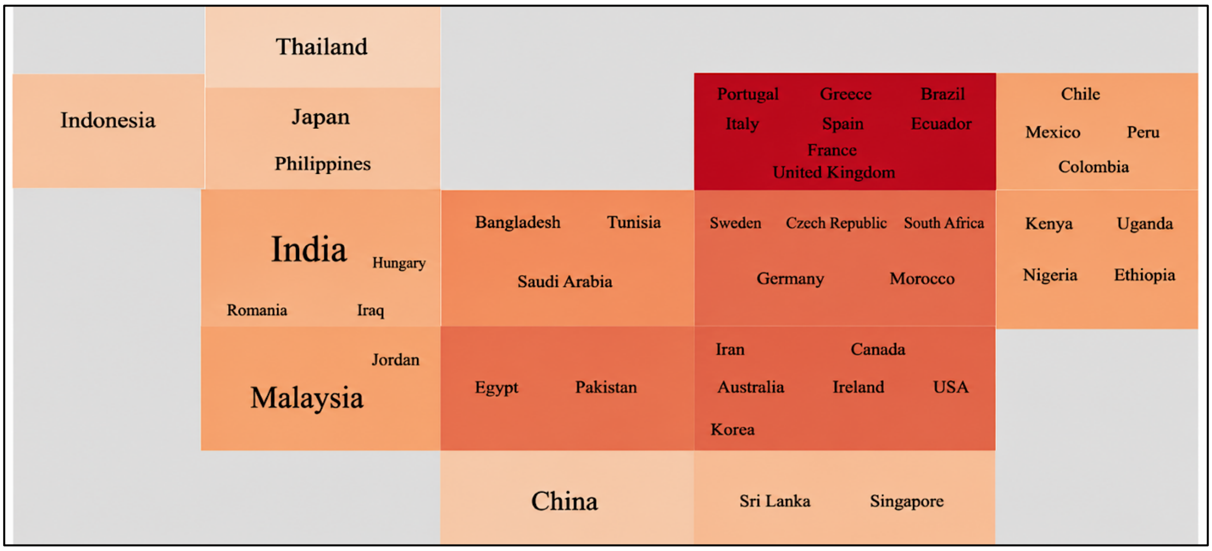

Figure 3: Collaboration Network Density of Countries in Iot Applications in Agriculture

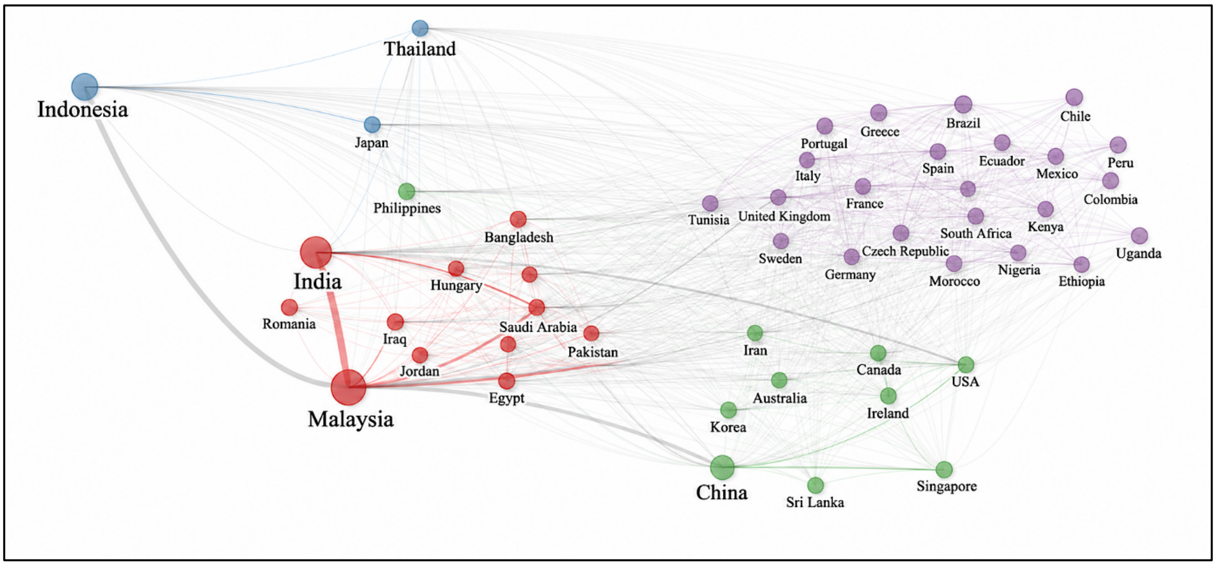

Figure 4: Country Collaboration Network and Cluster Structure in Iot Applications in Agriculture

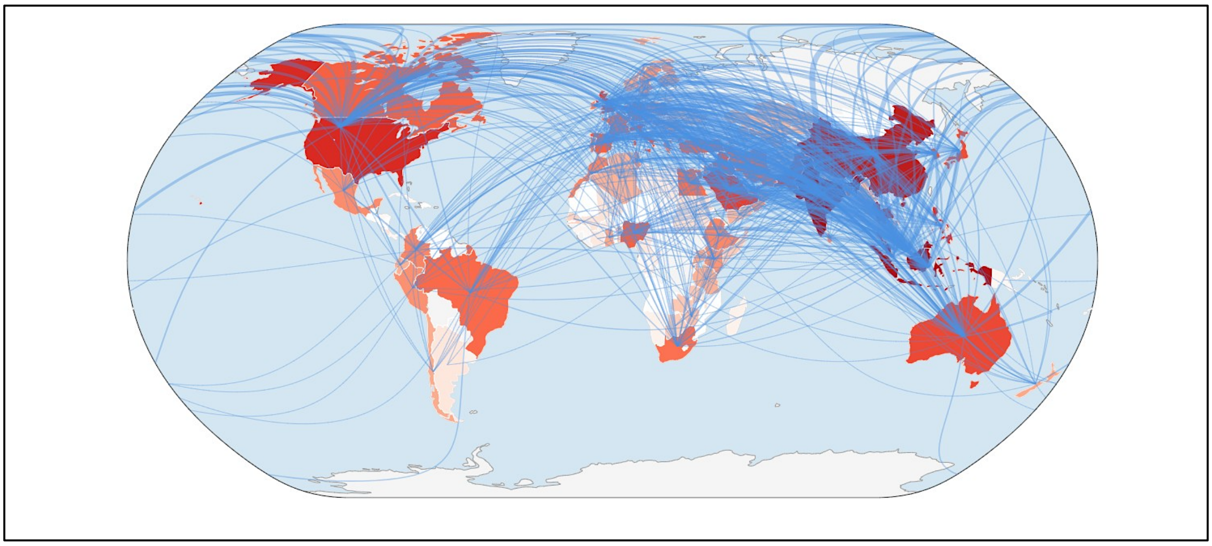

Figure 5: Global Collaboration Map of Countries in Iot Applications in Agriculture

The global dimension of these collaborations is presented in Figure 5, which highlights the geographic distribution of research partnerships in IoT-based agricultural research. The visualization shows that Southeast Asian countries maintain extensive linkages with external partners, particularly China, the United States and several European countries. These international collaborations facilitate knowledge exchange, technology transfer and access to broader research resources, thereby enhancing the visibility and impact of regional scientific outputs. However, intra-regional collaboration within Southeast Asia appears comparatively limited, suggesting that research cooperation among neighboring countries remains less developed than partnerships with external collaborators. This outward-oriented pattern is consistent with prior findings that developing regions often rely on international partnerships for research development and capacity building (41, 42). The observed collaboration structure further highlights the opportunity for ASEAN member states to strengthen regional research networks and promote greater scientific integration in support of sustainable agricultural innovation.

The distribution of research impact, as measured by citation counts, is presented in Figure 6. The results indicate a clear concentration of influence, with India leading by a substantial margin, followed by Malaysia and China. This concentration suggests that a small group of countries not only contributes a significant share of publications but also produces high-impact research that shapes the field, consistent with established citation distribution patterns in bibliometric studies (43-45). The dominance of these countries in citation performance may be attributed to stronger research ecosystems, greater investment in technological innovation and more extensive international collaboration networks. Higher citation counts also reflect the ability of these countries to generate influential studies that serve as important references for subsequent research. Consequently, the findings indicate that research leadership within IoT-enabled agriculture remains concentrated among a limited number of countries that play a pivotal role in advancing the intellectual development of the field.

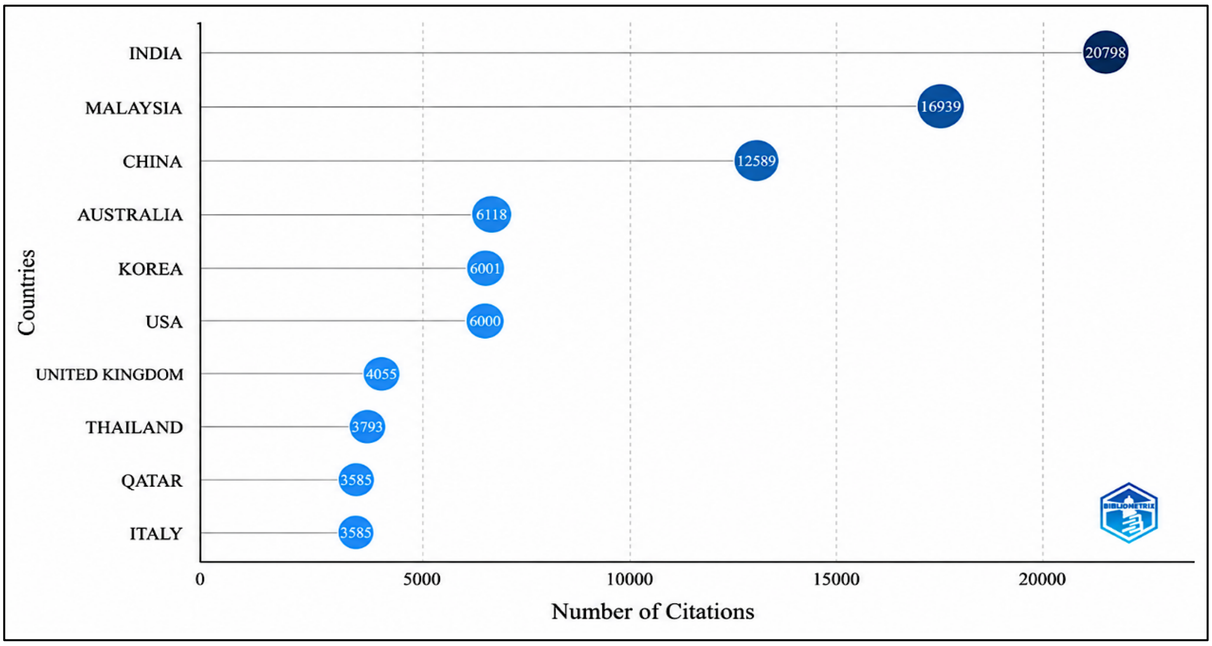

Figure 6: Most Cited Countries in Iot Applications in Agriculture

The dominance of countries such as India, Malaysia and China within the publication and collaboration networks may be attributed to a combination of technological readiness, research capacity and strategic policy support for digital agriculture. These countries have invested considerably in agricultural innovation, information and communication technologies and smart farming initiatives, enabling stronger integration between academic research and practical agricultural applications. Their central positions within the collaboration network further suggest the presence of established institutional partnerships and international research linkages that facilitate knowledge exchange and resource sharing. Conversely, the relatively limited research output and collaborative engagement observed in several Southeast Asian countries may reflect disparities in research funding, technological infrastructure and institutional capacity. These findings highlight the importance of strengthening regional cooperation and fostering inclusive research ecosystems to support the broader adoption of IoT-enabled agricultural innovations.

Additional insight into collaboration dynamics is provided in Figure 7, which distinguishes between Single Country Publications (SCP) and Multiple Country Publications (MCP). Countries such as Indonesia exhibit a relatively higher proportion of MCP, indicating a stronger reliance on international research partnerships for knowledge production and scientific exchange. In contrast, Malaysia demonstrates a more balanced SCP–MCP distribution, reflecting both robust domestic research capacity and active engagement in international collaboration. This balance suggests the presence of a mature research ecosystem capable of generating substantial local research outputs while simultaneously benefiting from global scientific networks. International collaboration has been shown to enhance research visibility, knowledge transfer and citation impact, underscoring the importance of MCP in strengthening scientific productivity and influence (46, 47). The patterns observed in Figure 7 further indicate that countries with stronger international engagement tend to occupy more prominent positions within the broader research network.

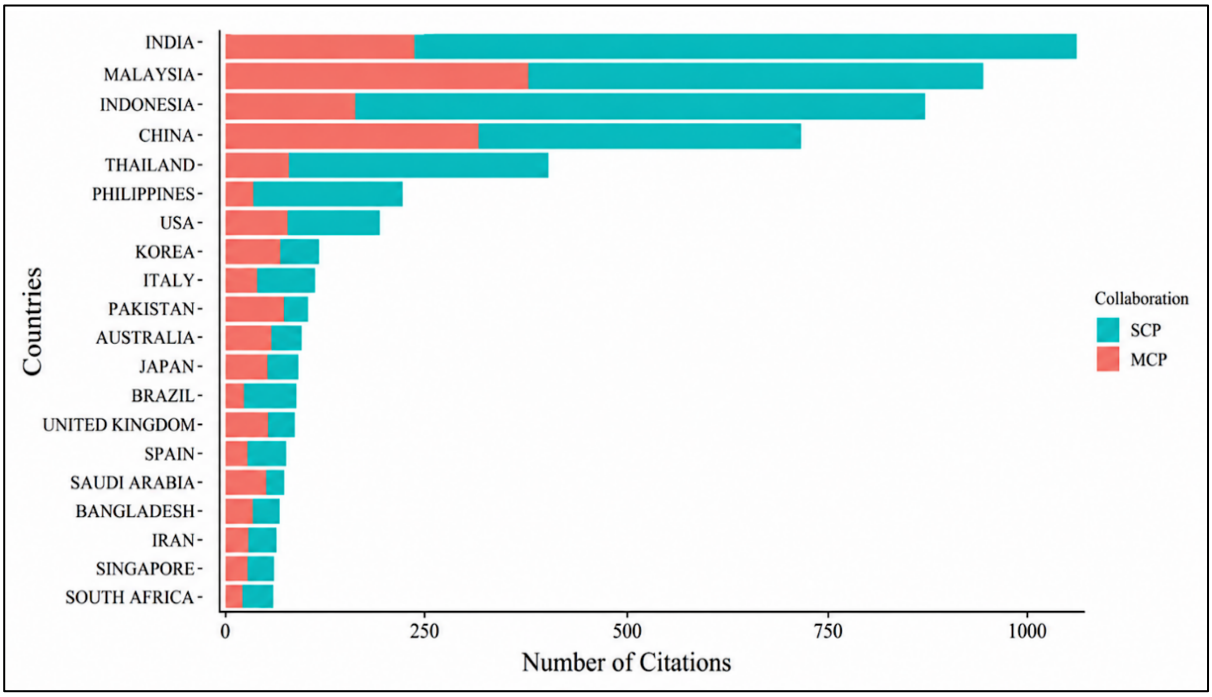

Figure 7: Corresponding Author Countries Based on SCP And MCP in Iot Applications in Agriculture
SCP=Single Country Publications, MCP=Multiple Country Publications

The centrality measures reported in Table 1 support these observations. India exhibits the highest betweenness centrality, highlighting its critical role as an intermediary connecting different research clusters and facilitating the flow of knowledge across the collaboration network. Malaysia records a comparatively strong PageRank value, indicating that it is closely connected to influential and highly productive countries, thereby reinforcing its position as a major research hub. The centrality indicators collectively demonstrate that scientific collaboration within the field is concentrated around a small number of strategically positioned countries that influence both knowledge dissemination and research connectivity. These findings further confirm the existence of a core–periphery structure, where a limited group of countries serves as key drivers of international collaboration and scholarly impact in IoT-based agricultural research (48).

Table 1: Collaboration Network Centrality Measures of Countries in Iot Applications in Agriculture

Node	Cluster	Betweenness	Closeness	Page Rank
India	1	87.242	0.02	0.08
Malaysia	1	62.861	0.019	0.101
Pakistan	1	13.016	0.02	0.04
Saudi Arabia	1	18.347	0.019	0.045
Iraq	1	1.979	0.015	0.02
Bangladesh	1	1.916	0.016	0.017
Turkey	1	2.992	0.017	0.017
Egypt	1	0.775	0.016	0.014
United Arab Emirates	1	2.339	0.017	0.02
Jordan	1	0.176	0.014	0.013

Further evidence from Table 2 shows that Southeast Asian countries, particularly Malaysia and Indonesia, rank highly in terms of corresponding authorship, demonstrating their growing leadership in IoT-based agricultural research. India remains the most productive country with 1,024 publications, followed by Malaysia [920] and Indonesia [852], indicating that research activity is concentrated among a relatively small group of highly productive nations. The relatively high proportion of Multiple Country Publications (MCP) observed in Malaysia, China and Pakistan further suggests strong engagement in international research collaboration, whereas countries with lower MCP percentages appear to rely more heavily on domestic research networks. These findings indicate that research productivity and international collaboration are closely intertwined and collectively contribute to the visibility, influence and leadership of countries within the field. Overall, the results point to a core–periphery structure characterized by concentration of influence, asymmetric collaboration patterns and limited regional integration. While Southeast Asia is emerging as a significant contributor to IoT-driven agricultural research, the relatively weak intra-regional collaboration highlights a critical gap. Strengthening ASEAN-level research partnerships, fostering cross-country collaboration initiatives and investing in regional research infrastructure will be essential to develop a more balanced, resilient and self-sustaining research ecosystem (49).

Table 2: Most Relevant Countries by Corresponding Author in Iot Applications in Agriculture in Southeast Asia

Country	Articles	Article P (%)	SCP	MCP	MCP P (%)
India	1024	10.5	792	232	22.7
Malaysia	920	9.4	550	370	40.2
Indonesia	852	8.7	692	160	18.8
China	705	7.2	395	310	44
Thailand	390	4	312	78	20
Philippines	211	2.2	177	34	16.1
Usa	187	1.9	112	75	40.1
Korea	114	1.2	48	66	57.9
Italy	109	1.1	71	38	34.9
Pakistan	104	1.1	32	72	69.2

Note: Article P (%) = percentage share of total publications; SCP = Single Country Publications; MCP = Multiple Country Publications; MCP P (%) = percentage of Multiple Country Publications.

Conceptual Structure and Thematic Clusters

The conceptual structure of the field is illustrated through the keyword co-occurrence network in Figure 8, which reveals a highly interconnected research landscape centered on the "internet of things" as the dominant theme linking multiple domains. The network structure highlights the co-existence of several major thematic clusters, reflecting the multidisciplinary nature of IoT-based agricultural research. The central position and extensive connections of the "internet of things" keyword indicate its role as the primary integrative framework that connects technological, environmental and agricultural research domains. Closely linked keywords such as precision agriculture, machine learning, artificial intelligence and smart agriculture further demonstrate the increasing convergence of sensing technologies, data analytics and automated decision-support systems. The density of relationships among keywords suggests a mature and evolving knowledge structure in which technological innovation is increasingly integrated with sustainability and resource-management objectives. These findings underscore the interdisciplinary character of the field and highlight the growing importance of data-driven approaches in addressing contemporary agricultural challenges.

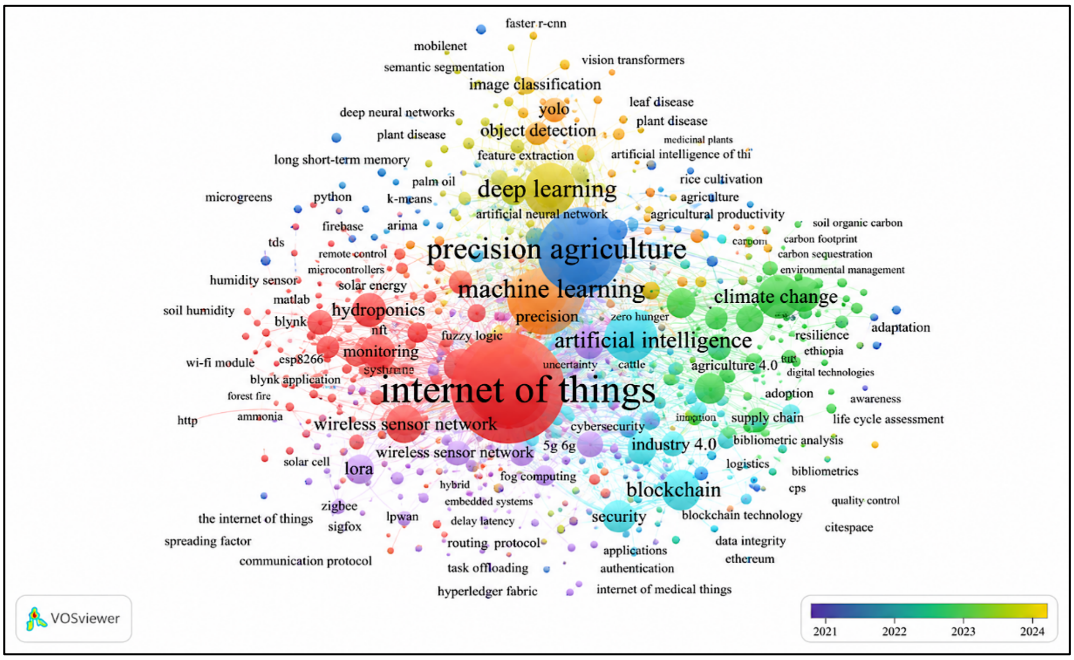

Figure 8: Keyword Co-occurrence Network

The first cluster focuses on IoT infrastructure, including wireless sensor networks, communication protocols and monitoring systems. These technologies form the backbone of smart agriculture by enabling real-time data acquisition and system integration. Prior studies have consistently demonstrated that wireless sensor networks are fundamental to precision agriculture and play a critical role in optimizing irrigation, soil monitoring and crop management (50, 51). The density and central positioning of these keywords in Figure 8 further confirm their foundational role in the research landscape. The second cluster centers on intelligent systems, characterized by the integration of Machine Learning, deep learning and Artificial Intelligence. This cluster reflects the increasing adoption of advanced analytics for predictive modeling, disease detection and yield optimization. The convergence of IoT and AI has been widely recognized as a transformative driver of modern agriculture, enabling automation and data-driven decision-making (52, 53).

The third cluster highlights sustainability and environmental management, encompassing themes such as climate change, carbon sequestration and adaptation strategies. This suggests a growing emphasis on leveraging IoT technologies to address global environmental challenges. Recent studies support this trend, emphasizing the role of smart agriculture in enhancing climate resilience, improving resource efficiency and promoting sustainable intensification (54). The fourth cluster represents emerging technologies, including Blockchain Technology, cybersecurity and Industry 4.0. These technologies extend IoT applications beyond farm-level production toward supply chain management and secure data exchange. Existing literature highlights that blockchain and Industry 4.0 frameworks significantly improve transparency, traceability and data integrity in agri-food systems (55-57). Overall, the strong interconnections among these clusters in the keyword co-occurrence network Figure 8 demonstrate that the field is inherently interdisciplinary, integrating engineering, data science and environmental science. This finding aligns with recent smart agriculture frameworks that emphasize holistic and system-oriented approaches to digital agriculture (58).

Thematic Evolution and Emerging Research Trends

The temporal evolution of research themes is illustrated by the keyword overlay visualization in Figure 9, which provides insight into how the focus of IoT-based agricultural research has shifted over time. Unlike the structural relationships shown in Figure 8, the overlay visualization highlights the chronological development of key topics. The color gradients indicate the progression of research interests from foundational themes related to sensing technologies, wireless communication and monitoring systems toward more advanced topics involving artificial intelligence, machine learning and intelligent decision-support systems. More recent keywords are increasingly associated with sustainability, climate resilience, resource optimization and digital transformation, reflecting the growing emphasis on addressing environmental and food security challenges through technological innovation. The visualization further demonstrates the dynamic nature of the field, where emerging technologies are continuously integrated into agricultural applications to enhance efficiency, productivity and sustainability. These temporal patterns suggest that IoT-based agricultural research has evolved from technology-oriented development toward more holistic and impact-driven approaches that combine technological advancement with sustainability objectives.

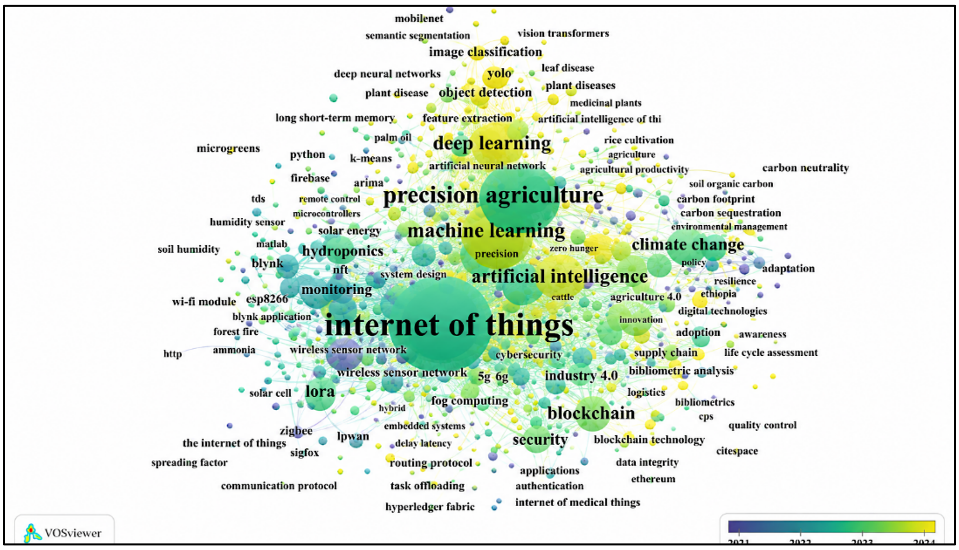

Figure 9: Keyword Overlay Visualization

The results indicate that early research was primarily concentrated on IoT infrastructure, including sensors, communication technologies and data acquisition systems. This initial phase established the technological foundation necessary for smart agriculture, as widely documented in early IoT adoption studies (59, 60). Subsequently, the research focus shifted toward intelligent systems, marked by the growing integration of Machine Learning and Artificial Intelligence into agricultural applications. This transition reflects the increasing demand for predictive analytics, automation and decision-support systems. Numerous studies have demonstrated the effectiveness of machine learning techniques in crop yield prediction, pest detection and precision farming optimization (61, 62).

More recent research trends highlight a strong shift toward sustainability and system-level innovation. Keywords related to climate-smart agriculture, environmental monitoring and resource efficiency dominate the most recent period in Figure 9. This aligns with global research priorities that emphasize sustainable agriculture and resilience to climate change (41, 63). Additionally, emerging topics such as Blockchain Technology and digital supply chain management indicate that research is expanding beyond farm-level applications to encompass entire agricultural ecosystems. Studies have shown that blockchain can enhance transparency, traceability and trust across agrifood supply chains (64, 65). The findings suggest that the field has evolved through three major phases: (a) infrastructure development,

(b) intelligent system integration and
(c) sustainability-driven innovation.

The temporal patterns observed in the keyword overlay visualization confirm the increasing maturity and complexity of IoT-based agricultural research. This evolutionary trajectory is consistent with prior bibliometric and review studies describing the progression of digital agriculture toward integrated, data-driven and sustainability-oriented systems (59).

Research Lifecycle and Field Maturity

The research lifecycle, as shown in Figure 10, follows a logistic growth pattern characterized by rapid expansion and an emerging stabilization phase. Figure 10A illustrates the annual publication trajectory, revealing a substantial increase in scientific output after 2018 and highlighting the accelerating adoption of IoT technologies in agricultural research, reaching a peak of approximately 2,090 publications in 2024 (R^2 = 0.879). This trend reflects the transition from an emerging to a maturing research field, consistent with established scientometric growth models (66). The inflection point observed around 2023–2024 in Figure 10, left suggests that the field is entering a consolidation stage, where foundational technologies have been widely explored. Similar patterns have been reported in studies on digital agriculture and smart agriculture, where rapid growth is followed by stabilization as research shifts toward refinement and application (67). The cumulative growth curve shown in Figure 10B further supports this interpretation, showing a characteristic S-shaped trajectory approaching a projected saturation level (K ≈ 10,122 publications). The gradual flattening of the curve suggests that although research output is expected to continue increasing, the rate of growth will likely slow as the field approaches maturity. The proximity to the upper asymptote indicates that future development will be characterized by incremental contributions rather than rapid expansion, with greater emphasis on refinement, application and specialization of existing knowledge (68).

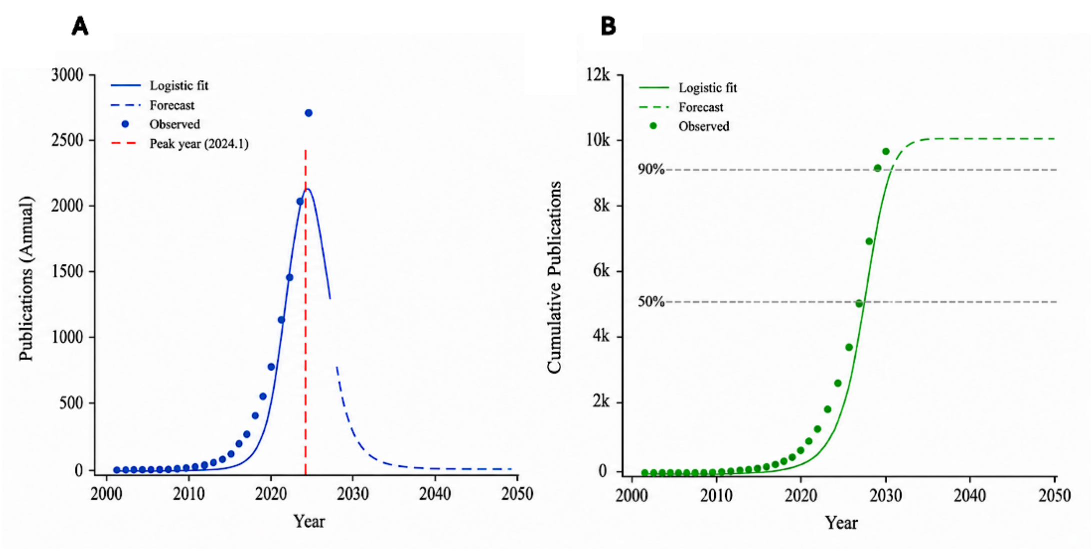

Figure 10: Research Lifecycle of Iot-based Agriculture. (A) Annual Publications with Logistic Growth Fit (B) Cumulative Publications Showing Saturation Trend

As the field matures, research is expected to move from exploratory development toward application-oriented and impact-driven studies, including scalability, system integration and real-world deployment. This transition aligns with the evolution of precision agriculture and the increasing integration of artificial intelligence in agricultural systems (61). For Southeast Asia, the maturity phase highlighted in Figure 10 presents an opportunity to prioritize implementation- focused research, particularly to address climate variability, resource constraints and food security challenges. This shift toward contextualized and scalable solutions is consistent with global directions in sustainable digital agriculture (54).

The lifecycle analysis suggests that IoT research in agriculture is transitioning from an expansion phase toward a more mature stage of development. Rather than indicating a decline in innovation, this transition may signify that foundational technologies have become increasingly established within the scientific community. As technological maturity increases, future advancements are likely to be driven less by hardware development and more by the integration of complementary technologies such as artificial intelligence, edge computing, digital twins and advanced analytics. Consequently, future research may place greater emphasis on scalability, interoperability, farmer adoption and measurable sustainability outcomes, reflecting a shift from technological feasibility toward practical implementation and societal impact.

Intellectual Structure and Theoretical Integration

The intellectual structure of the field is illustrated through the Multiple Correspondence Analysis (MCA) conceptual map, as shown in Figure 11, and the hierarchical clustering dendrogram in Figure 12. Together, these methods provide complementary insights into thematic relationships and the underlying theoretical dimensions of IoT-based agricultural research. Figure 11 reveals the distribution of major research themes across a conceptual space, highlighting how different topics are positioned and interconnected within the broader knowledge structure. The clustering pattern suggests that the field has evolved into a multidisciplinary domain where technological innovation, agricultural productivity and sustainability-oriented research increasingly converge. The MCA map further reveals two dominant conceptual dimensions. The horizontal axis (Dim 1) primarily reflects technological advancement, ranging from IoT infrastructure to advanced analytics such as Machine Learning and Artificial Intelligence. The vertical axis (Dim 2) captures the sustainability orientation, where topics such as climate-smart agriculture and food security are positioned distinctly from purely technical domains. This separation indicates that sustainability has emerged as a parallel and increasingly influential research trajectory, consistent with recent studies on digital agriculture (69, 70). IoT appears centrally positioned in Figure11, reinforcing its role as an integrative framework that connects the infrastructure, analytics and application layers. The proximity of terms such as precision agriculture, smart agriculture and remote sensing further suggests a strong conceptual convergence between sensing technologies and data-driven decision systems, as also highlighted in prior research (71).

Complementing the MCA results, the hierarchical clustering dendrogram, as shown in Figure 12, provides deeper insight into the intellectual organization of the field by identifying groups of closely related research themes based on keyword co-occurrence patterns. The dendrogram reveals several interconnected thematic clusters that collectively define the knowledge structure of IoT-enabled agriculture, including smart farming technologies, intelligent analytics, monitoring systems and sustainability-oriented applications. The relatively short linkage distances observed among several clusters suggest substantial conceptual overlap and knowledge exchange between research domains, indicating that advancements in the field increasingly depend on interdisciplinary integration. These findings demonstrate that IoT-based agricultural research is characterized by a highly interconnected intellectual structure in which emerging technologies, analytical approaches and sustainability objectives converge to address complex agricultural challenges and support the development of more resilient farming systems.

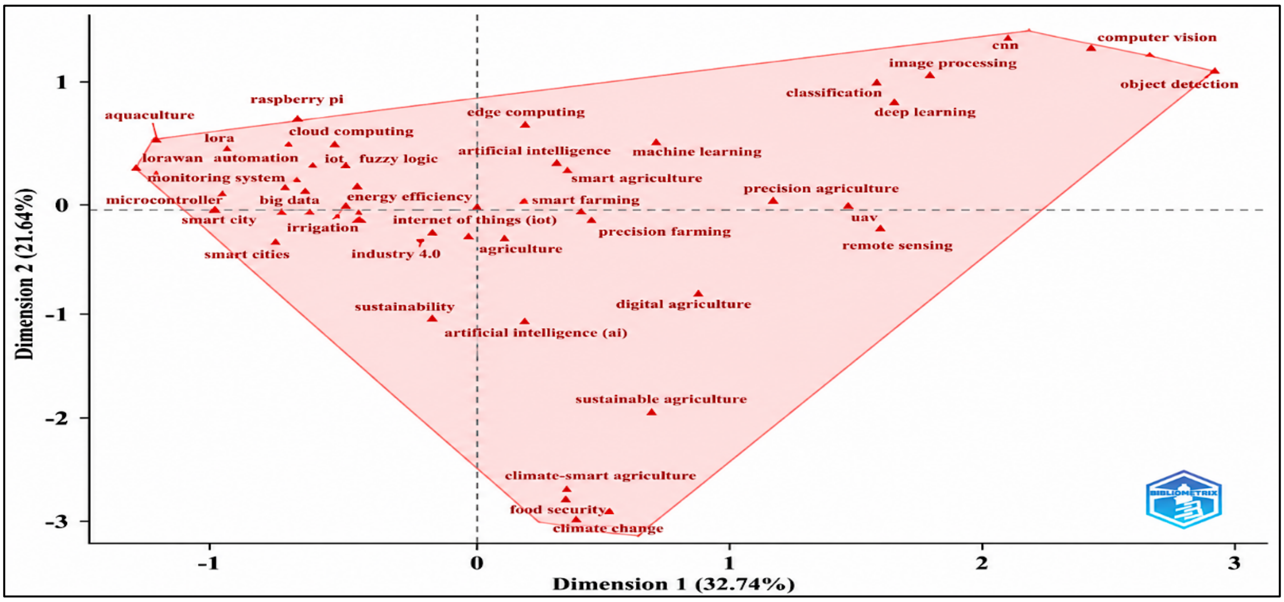

Figure 11: Conceptual Structure Map Based on MCA Showing the Distribution of Research Themes Across Two Dimensions

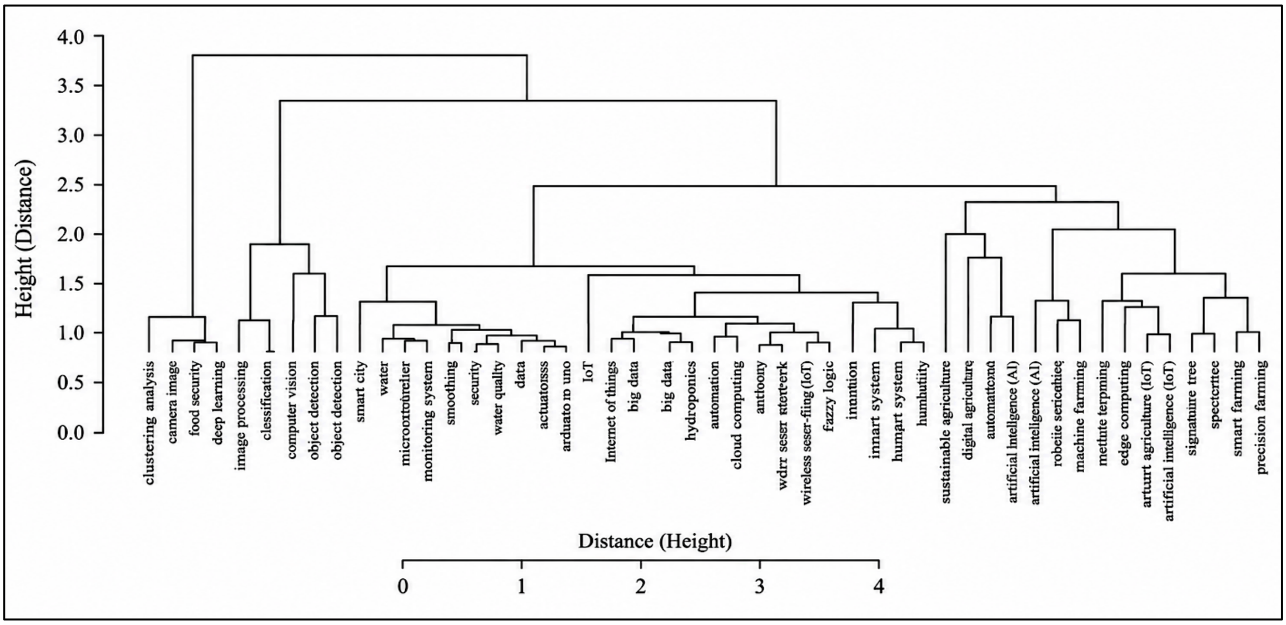

Figure 12: Hierarchical Clustering Dendrogram of Keyword Co-occurrence Showing the Intellectual Structure of Iot-based Agriculture Research

The hierarchical clustering Figure 12 complements this interpretation by identifying structurally coherent thematic groups. Four major clusters are evident:

a) infrastructure and communication technologies,
b) intelligent systems and analytics,
c) application domains such as precision agriculture and
d) sustainability and environmental management.

The relatively short linkage distances between clusters indicate strong interconnections, suggesting that the field is not fragmented but organized into closely related knowledge domains.

Conclusion

This study presents a comprehensive bibliometric analysis of IoT applications in agriculture, with particular emphasis on the development and research landscape of Southeast Asia. Through the integration of performance analysis, collaboration network mapping, conceptual structure analysis and lifecycle modeling, the study provides a holistic understanding of the field's evolution, intellectual structure and emerging research directions. The findings demonstrate a substantial increase in scholarly attention to IoT-enabled agriculture over the past decade, reflecting the growing importance of digital technologies in addressing agricultural productivity, resource management, sustainability and climate-related challenges. The results further reveal a transition from early research centered on sensing devices and connectivity infrastructure toward more advanced applications involving artificial intelligence, data analytics, automation and sustainability-oriented agricultural systems. In addition, the identification of India, Malaysia and China as influential contributors highlights the role of key regional actors in shaping research productivity, collaboration networks and knowledge dissemination within the broader agricultural technology ecosystem.

The study contributes to the literature by offering a region-specific perspective on the development of IoT-driven agricultural research, an area that remains comparatively underexplored in existing bibliometric investigations. By uncovering publication trends, thematic evolution, collaboration patterns and stages of technological maturity, the research advances understanding of how digital agriculture is progressing within Southeast Asia and its neighboring research networks. The findings also carry important practical and policy implications. The uneven distribution of research output and collaborative engagement across Southeast Asian countries suggests the need for stronger regional partnerships, targeted research capacity-building initiatives and enhanced knowledge-sharing mechanisms among academic institutions, govern-ments and industry stakeholders. Furthermore, the increasing prominence of sustainability-related themes underscores the potential of IoT technologies to support climate-resilient farming, improve resource-use efficiency, strengthen food security and facilitate evidence-based agricultural decision-making. These insights provide a valuable foundation for researchers, policymakers and practitioners seeking to accelerate the adoption and implementation of smart agricultural technologies across diverse agricultural contexts.

Despite its contributions, this study is subject to several limitations that should be considered when interpreting the findings. The analysis was confined to publications indexed within a single bibliographic database and may not fully capture relevant studies published in other databases, regional journals, conference proceedings, or emerging publication outlets. Moreover, bibliometric approaches are inherently limited to assessing patterns of scientific production and influence and do not directly evaluate the technical performance, socioeconomic outcomes, or practical effectiveness of IoT implementations in agricultural settings. Future research should therefore expand the scope of analysis by incorporating multiple databases, employing complementary scientometric techniques and conducting comparative regional assessments to provide a more comprehensive understanding of global and regional developments. Further investigation is also needed to examine the real-world impacts of IoT technologies on agricultural productivity, sustainability performance, farmer adoption and policy effectiveness, while exploring emerging areas such as AI-enabled IoT systems, edge computing, digital twins, precision agriculture and climate-smart farming solutions. Collectively, these efforts will contribute to a deeper understanding of the evolving digital agriculture landscape and support the development of more sustainable, resilient and technology-driven agricultural systems in Southeast Asia and beyond.

Abbreviations

AI: Artificial Intelligence, IoT: Internet of Things, MCA: Multiple Correspondence Analysis, MCP: Multiple Country Publications, SCP: Single Country Publications, VOS: Visualization of Similarities.

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Author Contributions

Franklin M Ganancias: Conceptualization, Methodology, Analysis, Jehu Roeh C Rubenial: Validation, Formal Analysis, Writing – Review Editing, Fae Mylene M Etchon: Data Curation, Writing - Original Draft Preparation, Sharon A Bucalon: Resources, Analysis, Writing – Review Editing, Lyndon A Rosas: Visualization, Writing – Review Editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Dataset will be made available on request.

Declaration of Artificial Intelligence (AI) Assistance

The authors used Grammarly and ChatGPT to assist with grammar checking, spelling correction and improvements in language clarity during the preparation of this manuscript. All intellectual content, research design, data analysis, interpretation of results and final decisions regarding the manuscript remain the sole responsibility of the authors. The authors carefully reviewed and edited all AI-assisted outputs to ensure their accuracy and appropriateness.

Ethics Approval

This study is based on bibliometric analysis of publicly available data and does not involve human participants, animal subjects, or personal data. Therefore, ethical approval and informed consent were not required. The authors confirm that the research was conducted in accordance with standard academic and ethical guidelines, including proper citation of sources and accurate reporting of findings.

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