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Discovering Research Landscape and Emerging Trends of Compost Implementation with the Internet of Things *via* Bibliometric Analysis

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ABSTRACT

This study explores the research landscape, emerging composting trends, and the Internet of Things (IoT) application via a comprehensive bibliometric analysis. The analysis examines 353 research documents from 2016 to 2024, identifying key themes, prominent authors, institutions, and countries in this evolving field. The results highlight the significant role of countries in Asian regions like India, China, and Malaysia as leading contributors to IoT-integrated composting research. These countries publish work focusing on smart waste management, biomass monitoring, and the application of artificial intelligence in optimising compost processes. Co-occurrence networks and thematic analyses emphasise IoT-based monitoring systems, renewable energy solutions, and machine learning applications. This study contributes to the existing literature by providing a systematic review of the integration of IoT with composting and identifying research gaps in the related field. The findings highlight the transformative potential of IoT in promoting sustainable agricultural practices and optimising waste management processes.

1. Introduction

The total global waste is projected to increase significantly with an estimated 46 billion tonnes by 2050 [1]. The growing concern for sustainability worldwide has made the quest for sustainable agricultural measures more stringent. Composting is a relevant organic waste management method because it enhances the soil structure, improves water retention, enriches soil organic matter, and increases nutrient content [2]. The use of compost as a soil amendment has been shown to significantly increase crop yields across recent studies. Kekong [3] reported that cocoa pod husk compost increased corn yield by improving soil pH and nutrient levels. Spent mushroom compost

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and municipal waste compost have been shown to affect soil fertility and yields of wheat, barley, and sugarcane [4,5]. Besides, compost could improve economic returns by enhancing produce quality [6] and reducing environmental pollution [7].

The Internet of Things (IoT) has emerged as a promising innovation for the agricultural challenges in the modern era. As noted by the McKinsey Global Institute, the economic impact of IoT technologies is projected to be $11.1 trillion by 2025 [8]. IoT technologies allow real-time monitoring of essential parameters during composting such as temperature, humidity, and oxygen level. IoT-based systems optimise these parameters by providing more efficient decomposition and better-quality compost [9,10]. Automating these systems can cut labour costs and increase the scalability and sustainability of the composting process [11]. Applying sensors in compost production is beneficial, although the decomposition process can be irregular due to uneven aeration, temperature changes and moisture control [12].

IoT technologies have transformed various traditional agriculture areas into precision farming worldwide. For instance, IoT sensors in smart farming systems can provide critical data to optimise water usage and monitor plant health [13,14]. Livestock management systems incorporating IoT-based monitoring can track animal health, monitor environmental conditions, improve resource efficiency, and reduce waste [15]. Integrating IoT and agriculture production is required when the global food demand is increasing drastically and natural resources are continually depleting [16]. Smart agriculture production would help optimise agriculture production and make more sustainable resources available for population growth and climate uncertainties [17]. Studies have shown that IoT applications in composting could lead to significant advancements in waste management. However, the literature lacks comprehensive analyses that explore the full potential of IoT in optimising the composting process [18,19]. To address this gap, the current study aims to conduct a bibliometric analysis to uncover emerging trends in composting and IoT. This bibliometric approach will analyse key trends, research collaborations, and the most influential works in IoT technologies and composting practices. Specifically, the study aims to answer the following key research questions; (1) What are the prevailing research trends in composting and IoT?, (2) Who are the prominent authors and leading countries in these fields?, and (3) What are the current research hotspots and emerging topics in compost and IoT studies?.

2. Methodology

2.1 Data Source and Collection

The data for this study was retrieved from the Scopus database through the OpenAthens gateway provided by Universiti Malaysia Kelantan on 1st October 2024. The Scopus database is suitable for bibliometric analysis due to its comprehensive coverage of multidisciplinary research and its robust citation [20]. To comprehensively capture relevant literature, we performed a systematic search using specific keywords related to compost and the IoT. Boolean operators, phrase searching, truncation, and synonyms word were applied within the Title-Abstract-Keywords search fields to ensure precise retrieval of relevant documents. A flow diagram illustrating the search strategy for identifying relevant publications is presented in Figure 1.

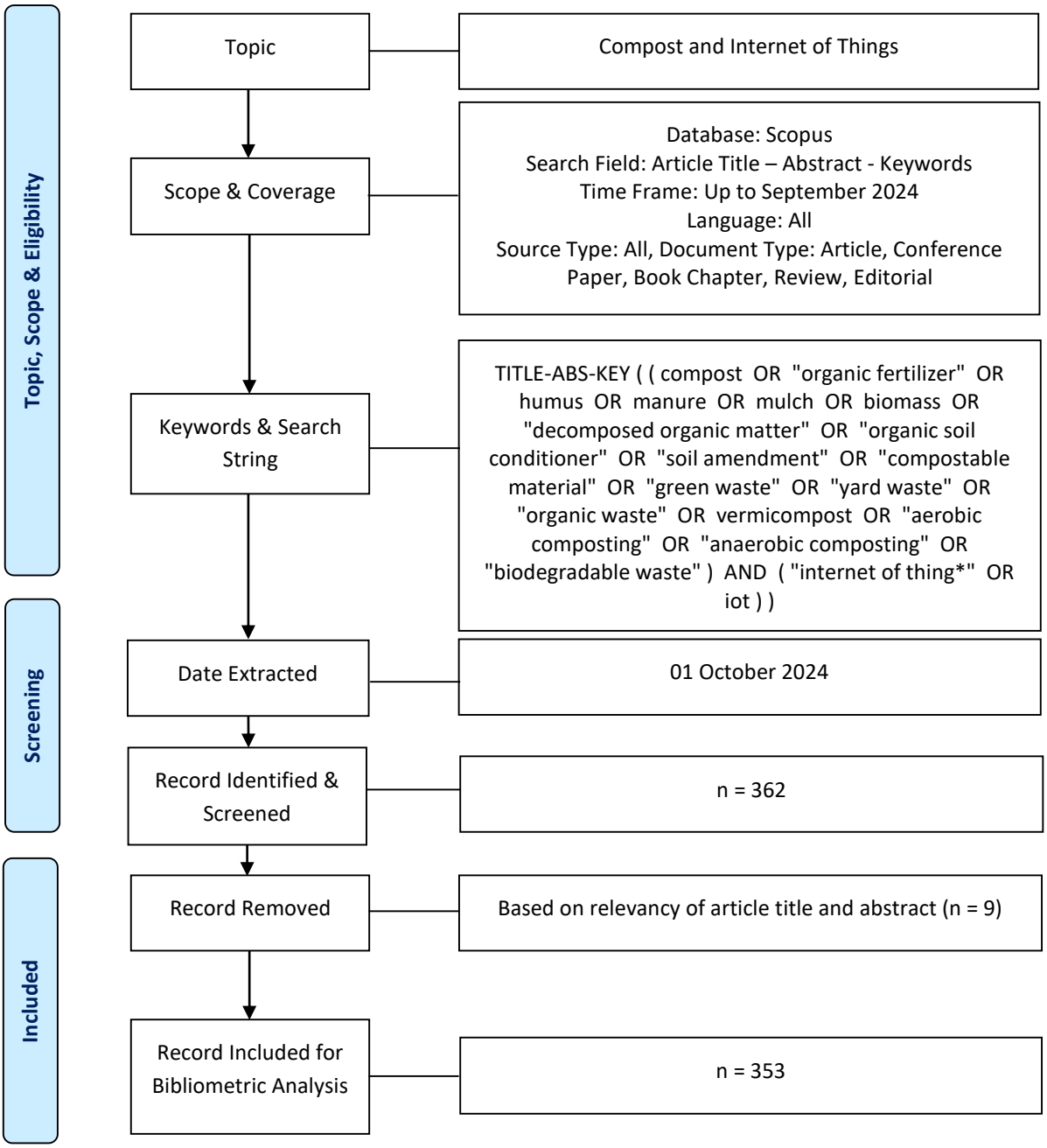

Fig. 1. Flow diagram of the search strategy of the relevant publications

2.2 Data Extraction and Visualisation

The metadata from the selected articles covering citation data, abstracts, keywords, and bibliographic information was exported in CSV format for analysis. The first stage of data screening was carried out by looking at the time frame and document type. The second screening stage involves the title and abstract relevancy of the domain area of study. Following data extraction, the bibliometric analysis was performed using the Bibliometrix package in R [21]. The research trends analysis focuses on annual scientific production and keyword co-occurrence to get an overview of the major developments in the research area. For emerging trends analysis, keyword growth, trending topics and thematic map were deployed to uncover the most rapidly growing research areas and identify potential hotspots for future exploration. The Biblioshiny interface was employed to streamline the analysis for dynamic visualisations and interactive dataset exploration. Network

visualisations are particularly effective for visualising large bibliometric networks and identifying clusters of interconnected topics [22] for a comprehensive understanding of the research landscape. The figures were generated using R and Microsoft Office Excell (Microsoft 365, Version 2409).

2.3 Data Cleaning

Before conducting the bibliometric analysis, the data underwent a cleaning process. Duplicate records were identified and removed to avoid bias in the analysis. Titles and abstracts were manually reviewed to ensure the selected documents were relevant to the research objectives. The PRISMA guidelines were followed to ensure transparency and replicability in the selection process [23]. The dataset was standardised to resolve inconsistencies in author names and keyword variants.

3. Results

3.1 Overview of Research Publications

Table 1 shows the key bibliometric indicators related to compost and IoT research extracted from the dataset from 2016 to 2024. The dataset encompasses 268 sources and 353 documents, indicating that the research on composting and IoT has grown steadily over the past eight years. The growing number of sources and documents indicates a rising interest in integrating IoT technologies with composting. The average publication year of 41.7 shows that the documents in this dataset are relatively recent and reflect advancements in IoT and environmental science [24]. Average citations per document (2.34) and average citations per year per document (7.575) further illustrate the emerging nature of this research field. Despite being a growing field, the low citation count suggests that many studies are relatively new and have not yet had time to accumulate significant citations. According to Rajak *et al.,* [25] this pattern is common in rapidly evolving fields where publications take time to influence the broader research community. The dataset contains 12,676 references, demonstrating the extensive bibliographic scope of the studies and reflecting the interdisciplinary nature of composting and IoT research.

Table 1
The main information of the bibliometric indicators of the extracted dataset

Description	Results
Timespan	2016-2024
Sources (Journals, Books, etc)	268
Documents	353
Average years from publication	41.7
Average citations per document	2.34
Average citations per year per doc	7.575
References	12676
Keywords Plus	2887
Author's Keywords	1083
Authors	1530
Authors of single-authored documents	13
Single-authored docs	14
Co-Authors per Doc	4.75
International co-authorships (%)	18.7

An examination of the keywords reveals 2,887 "keywords plus" and 1,083 author keywords, which signify diverse thematic interests in the research landscape focusing on smart farming, environmental monitoring, and soil health improvement. Bermudez *et al.,* [26] suggested that the

diversity in keywords highlights the multifaceted nature of IoT applications in agriculture. These technologies encompass various disciplines, from sensor technology to waste management. The dataset includes contributions from 1,530 authors, indicating active research collaboration within this domain. As noted by Senoo et *al.,* [27] the complexity of IoT systems requires interdisciplinary collaboration among experts in engineering, agriculture, and environmental science.

3.2 Publications Growth

Figure 2 illustrates the steady increase in annual publications and research trends related to compost and IoT from 2016 to 2024. This growth reflects the rising interest in using IoT technology to optimise composting processes. Bermudez *et al.,* [26] emphasise that low-cost IoT sensors are increasingly used to monitor compost parameters and demonstrate the potential of IoT in waste management and agriculture. The surge in publications from 2021 onwards aligns with the rising focus on smart agriculture [28]. This rapid growth indicates a strengthening global interest in integrating technological advancements with composting practices to improve environmental sustainability and agricultural efficiency.

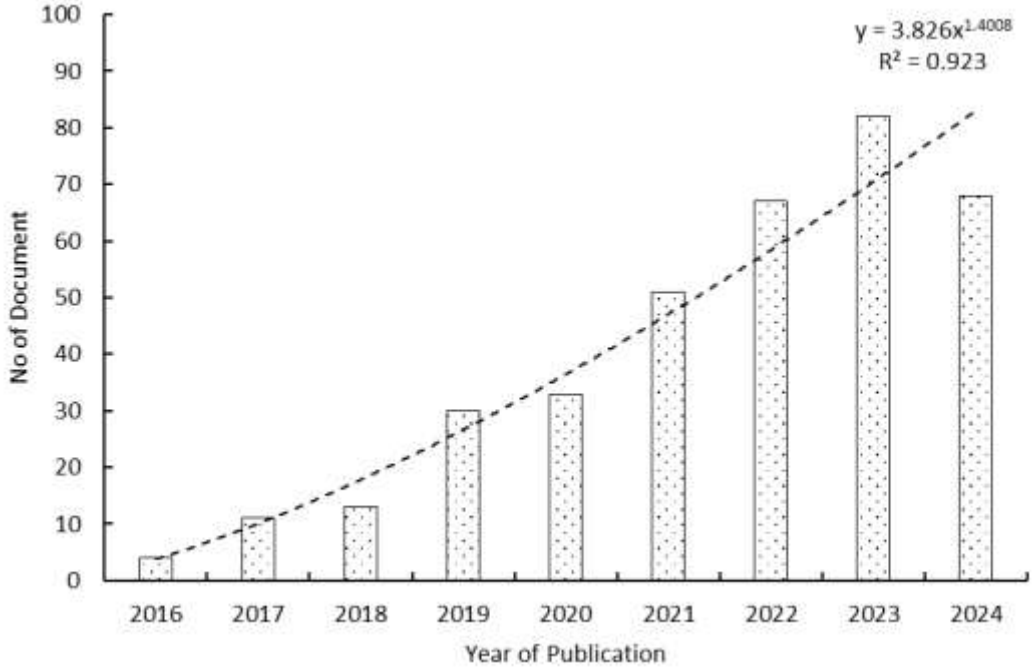

Fig. 2. Annual publication trends from 2016 until 2024

Figure 3 presents the annual trends in publication document types related to composting and IoT from 2016 to 2024 where a significant increase is evident in articles and conference publications. Articles are the most published document type, with a peak in 2022 and 2023, highlighting the crucial role of peer-reviewed journals in disseminating research findings. Book chapters and review articles show a steady rise, which reflects the growing need for comprehensive syntheses of the rapidly expanding research in this field. Editorials remain limited, indicating a lack of reflective commentary on published articles. One factor contributing to the growing research interest in composting includes the availability of materials that can be quickly produced from kitchen waste [29]. Margaritis *et al.,* [30] noted that household food waste can be converted into valuable compost within 21 days using simple and easily accessible materials, making it an ideal practice for domestic use. Additionally, compost offers an environmentally friendly solution that enhances soil health efficiently and cost-effectively [31,32].

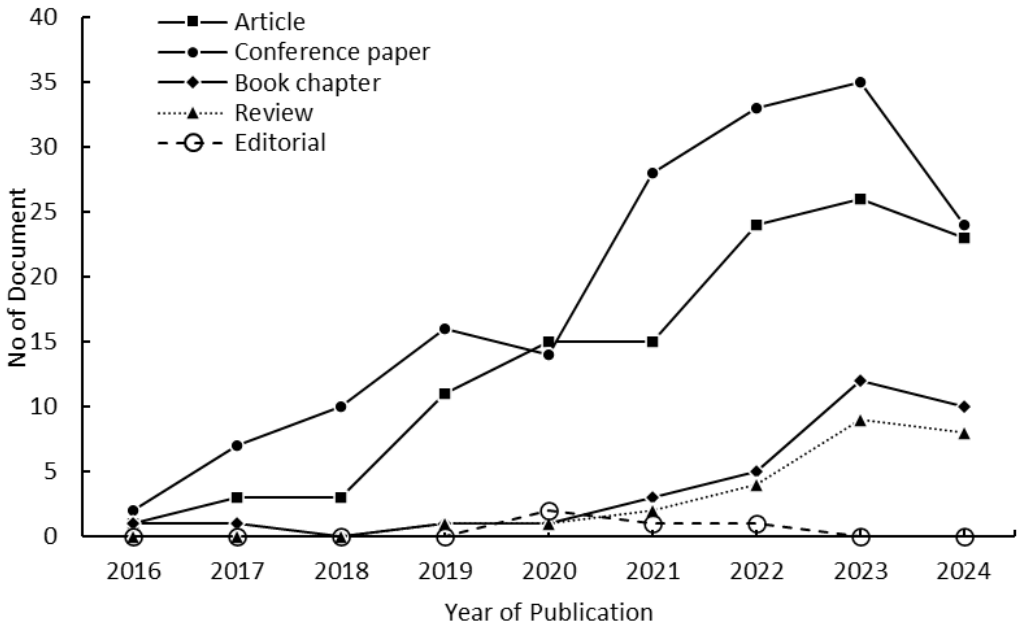

Fig. 3. Annual publication document type trends

Figure 4 presents the total number of citations received by documents related to composting and IoT from 2016 to 2024. The main observation is a significant rise in citations starting around 2019 and continuing to increase during the COVID-19 pandemic era. This trend reflects the growing academic interest and influence of publications in this research field during this period. The gradual decline in citations after 2022 may indicate a shift in research focus or saturation of specific topics. This trend reflects changes in scholarly discussions related to composting and IoT and may create opportunities for new research to revive interest. However, citations could increase in the future as cumulative citation counts depend on the time they are gathered. The observed trends indicate a possible shift towards integrating digital technologies into traditional fields like composting and agriculture and may explain the decline in citations for older research topics [33-35]. In addition, the COVID-19 pandemic resulted in an unexpected increase in research publications, particularly in life sciences and biomedicine despite external challenges such as geopolitical tensions that significantly reduced collaborations between some countries. Rousseau *et al.,* [36] highlight the scientific community's resilience and adaptability during global crises and the impact of political factors on international research collaborations.

The radar diagram (Figure 5) showcases the average citation metrics per year, divided into three categories: Mean Total Citations per Article (MeanTCperArt), Mean Total Citations per Year (MeanTCperYear), and the number of Citable Years. From 2016 onwards, there is a clear decline in the average citations per article after an initial high, with a notable drop in the following years. This could be attributed to a limited number of early publications in the composting and IoT fields that garnered substantial attention due to their novelty. The diagram suggests that the most significant impact occurred during the early phase of the study's timespan. By 2020, the average citations per year began to recover, aligning with the growing interest in smart agriculture and IoT applications. The radar's shape shows fluctuations in citable years, particularly in 2018 and 2020. Agriculture has evolved into a modern and sophisticated field integrating current technologies. The current progress in agriculture is significantly driven by rapid advancements in deep learning and the IoT that enhance precision farming through more efficient pest detection, disease management, and yield optimisation [37,38].

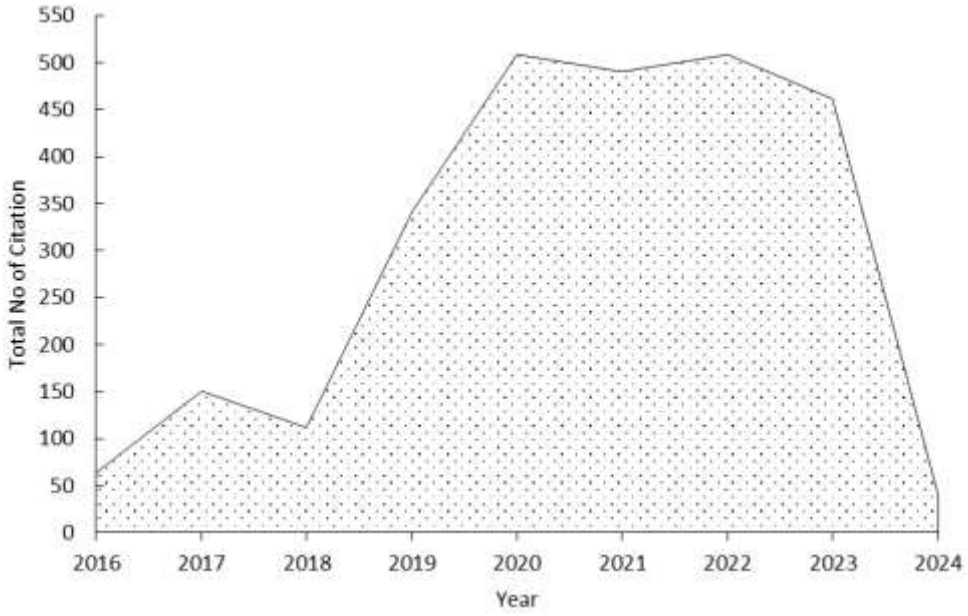

Fig. 4. Annually citation of document trends

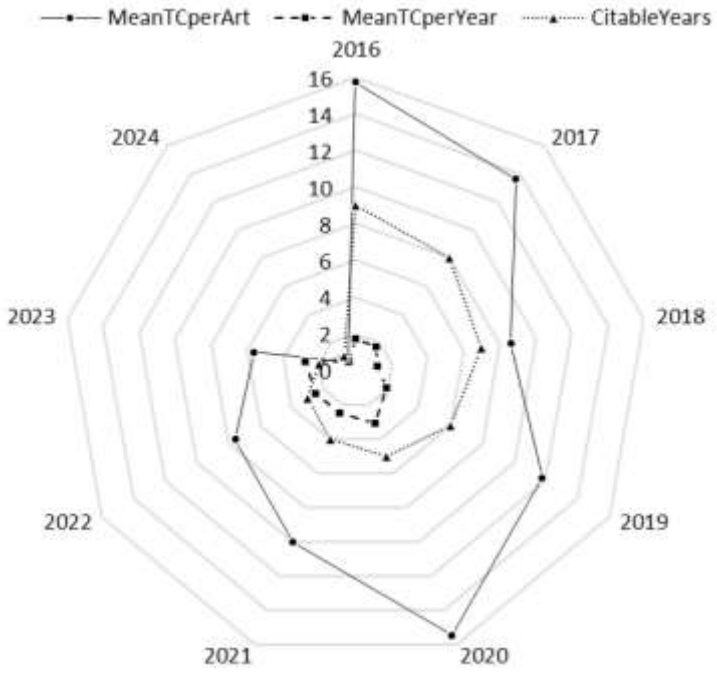

Fig. 5. Radar diagram of average citation per year

3.3 Most Productive Authors, Institutions and Country

Figure 6 illustrates the top 10 most productive authors over time. Among these, Wang Z., Chew KW, and Show PL stand out for their continuous contributions to IoT-based agricultural solutions. Wang Z. maintains consistent productivity from 2019 to 2023, contributing pivotal studies on the integration of IoT systems in optimising compost processes and agricultural outputs. Similarly, Chew KW and Show PL have seen their work gain recognition, especially in automated environmental monitoring using IoT networks. A key trend is the increasing number of citations for Chew KW and Show PL in 2023, reflecting the growing impact of their research on IoT-enabled smart farming. This

aligns with broader research efforts highlighting the role of IoT in enhancing agricultural productivity by reducing human intervention and improving precision in data collection and analysis [39].

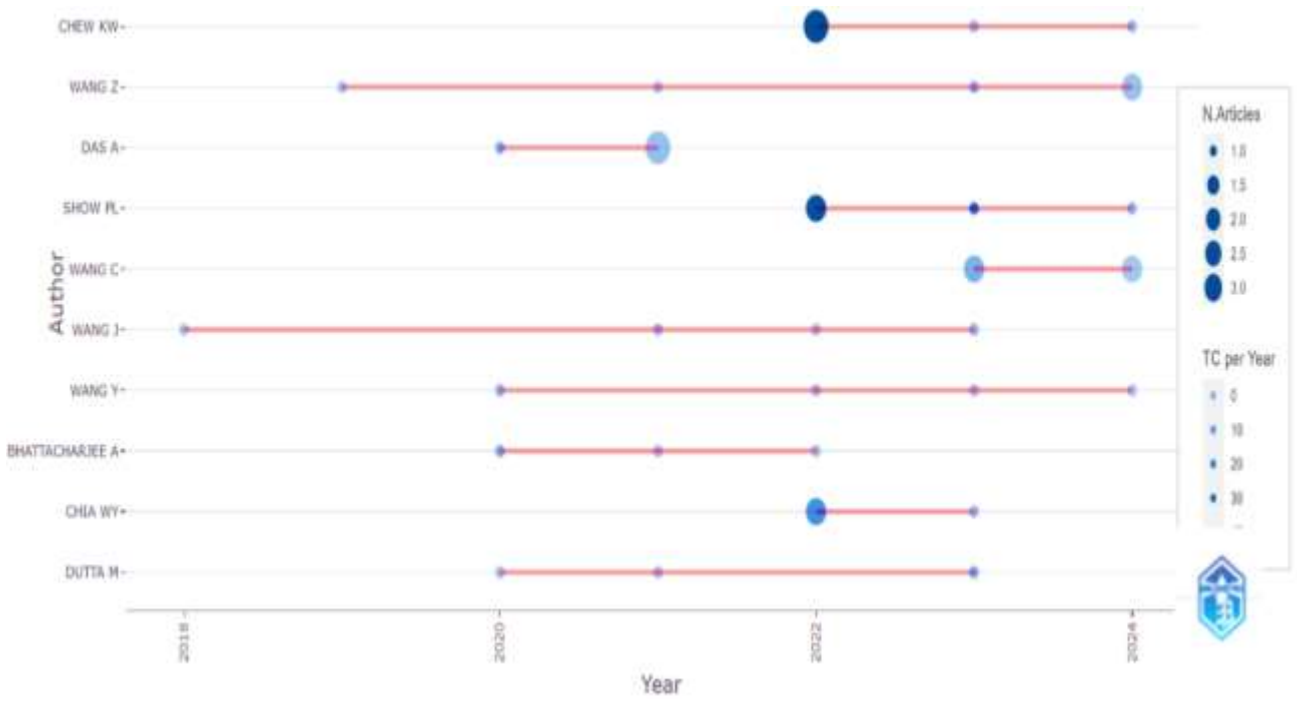

Fig. 6. Top 10 most productive authors over time

Figure 7 showcases a three-field plot connecting the most productive institutions, countries, and keywords. Leading institutions like the Free University of Bozen-Bolzano and the Institute of Cotton Research have been key players in driving IoT-related research in composting and IoT-related research. Countries like India, China, and Italy have emerged as leading contributors, showing a growing global interest in smart agriculture and composting technologies. Most listed countries are from Asia and play a pivotal role in driving innovation and collaboration in this research area. Countries such as India, China, and Malaysia have become central hubs reflecting their leadership in advancing IoT technologies for composting and sustainable agriculture. Their significant contributions demonstrate the region's commitment to integrating smart technologies to enhance agricultural practices and waste management systems globally. For example, studies from India have led the way in developing IoT-based monitoring systems to optimise waste management processes and improve agricultural outputs. This aligns with research highlighting India's focus on sustainable farming practices through IoT integration [40].

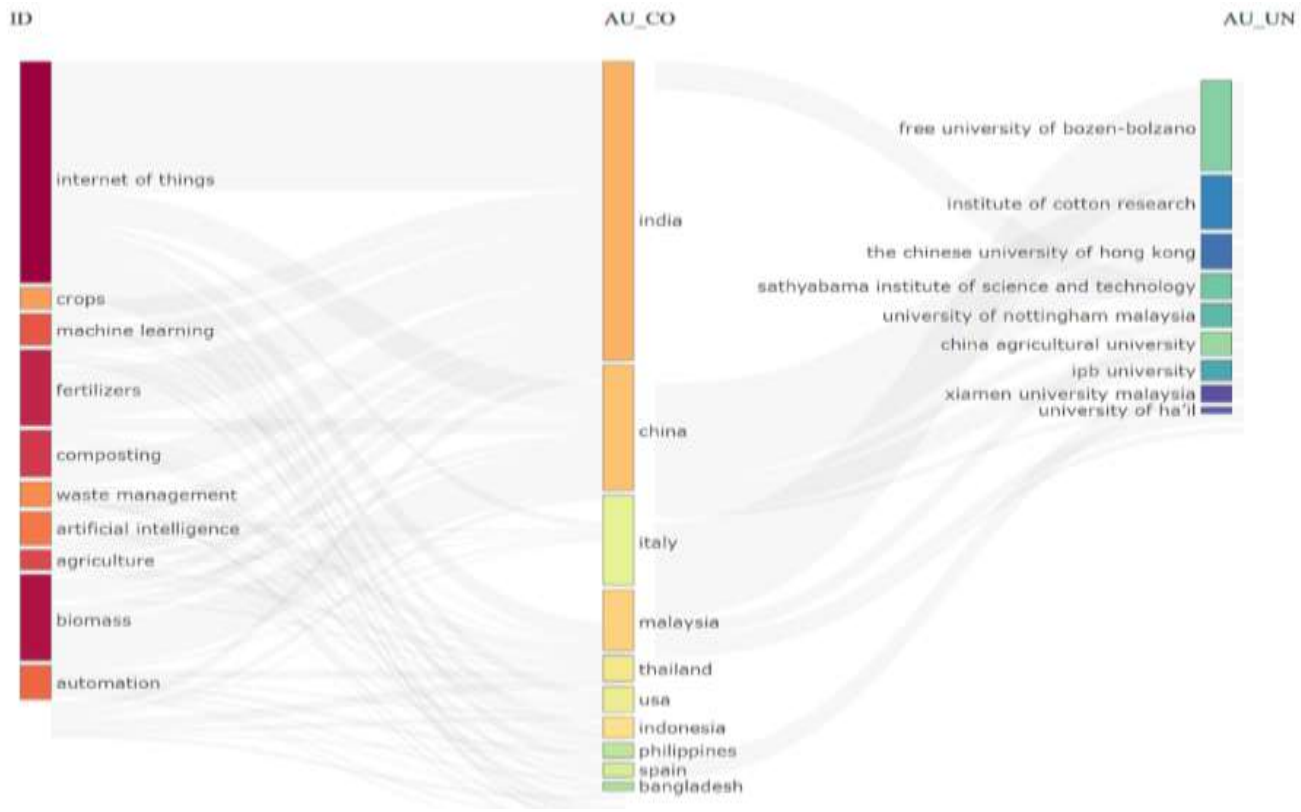

Fig. 7. Three field plot based on author country (n=10) at the middle, keyword plus (n=10) at the left and author affiliation (n=10) at the right

Figure 8 maps the global author collaboration networks in composting and IoT-related research. India, China, Malaysia, and the United States are shown as central hubs of international collaboration. India has been instrumental in fostering cross-border partnerships by collaborating with countries such as Italy and China to develop IoT solutions for agricultural sustainability. This reflects the growing importance of international research efforts in addressing the global challenges of waste management and sustainable agriculture. China and Malaysia play important roles in research on automating composting using IoT systems. Malaysian studies on vermicomposting show that automated systems improve composting by keeping ideal conditions, reducing manual work, and increasing efficiency [41]. These collaborations are essential for expanding global knowledge and creating sustainable composting solutions that can be scaled and applied in various agricultural areas.

Fig. 8. Map of the author collaboration between countries

3.4 Co-occurrence Network

Figure 9 displays the co-occurrence network of the most frequently used keywords to visualise recurring topics and themes in the research on IoT and composting. The visualisation reveals two distinct clusters: one focusing on “IoT-based monitoring systems” (red cluster) and the other on “smart waste management” (blue cluster). Key keywords like "IoT," "system," and "monitoring" indicate that the research focuses on developing and applying IoT systems for real-time monitoring and control in agricultural environments [42]. The prominence of monitoring and systems reflects the role of IoT technologies in automating and optimising composting processes. Study by Lavanya *et al.,* [43] demonstrate the use of IoT systems to monitor essential parameters like nutrient levels, temperature, moisture, and gas emissions, which are crucial for maintaining optimal environmental conditions. These systems reduce human involvement, enhance operational efficiency, and improve compost quality.

The blue cluster highlights keywords such as "smart," "waste," and "management," indicating a strong emphasis on advanced waste management in research. This aligns with trends in sustainable agriculture and waste recycling, where IoT technologies are employed to improve waste management efficiency. For example, IoT-enabled smart waste management systems are increasingly used to monitor and process waste in real-time [41]. These systems effectively manage resources by making composting processes both cost-efficient and environmentally sustainable [39]. The red cluster highlights "biomass" as a key keyword associated with the use of IoT for monitoring and optimising biomass in composting processes. Biomass is a primary source of organic waste and is increasingly monitored through IoT systems to optimise decomposition and enhance nutrient recycling in agricultural systems [44,45]. IoT-based biomass monitoring systems track the progress of organic matter decomposition to ensure the composting process is efficient and effective.

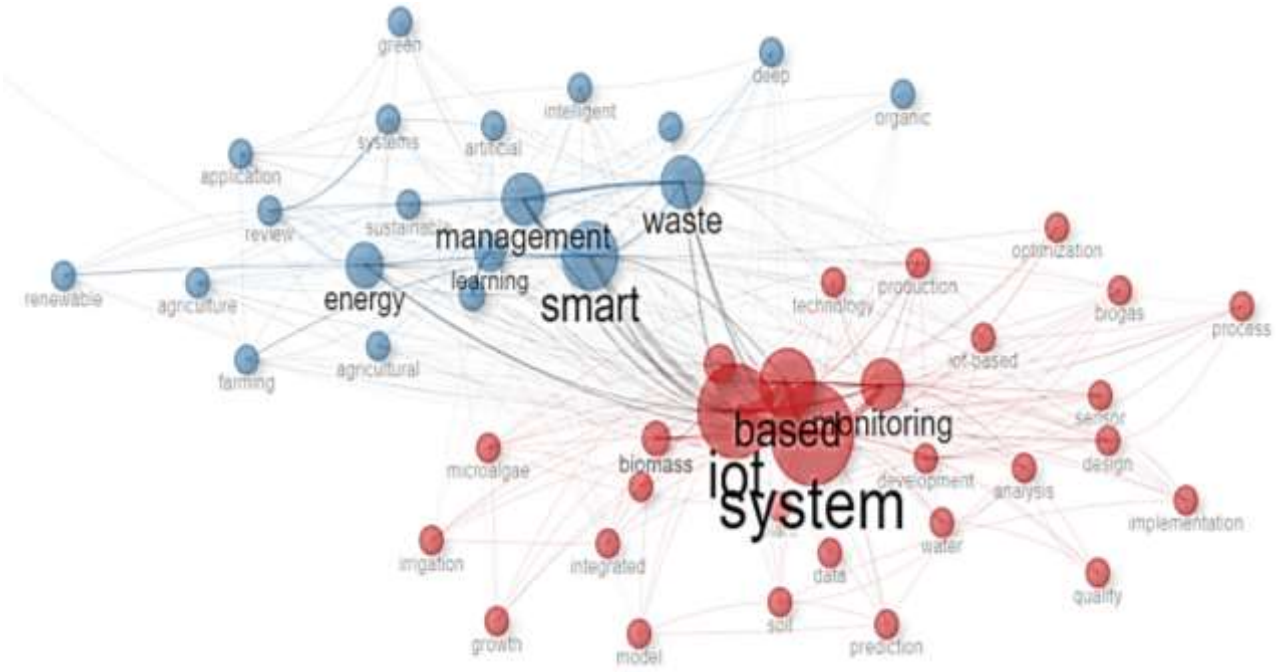

Fig. 9. Co-occurrence network between keywords

3.5 Emerging Topic in the Research Domain

The treemap diagram (Figure 10) illustrates the 20 most important keywords in the research area. “Internet of Things” dominates the treemap, representing 27% of the total keywords and reflects the increasing integration of IoT technologies in composting and agricultural applications. The strong presence of keywords like “fertilisers” (9%) and “biomass” (9%) further demonstrates the research community’s focus on utilising IoT to optimise agricultural inputs and manage organic waste efficiently [46]. The focus on IoT demonstrates how technology is revolutionising traditional farming and composting practices by enabling real-time monitoring and automation to achieve more efficient processes [47]. The inclusion of “machine learning” (4%) and “artificial intelligence” (3%) indicates the growing trend of combining IoT with advanced data analytics techniques to enhance decision-making processes. Research in this area highlights the role of machine learning algorithms in predicting optimal composting conditions to improve the quality and accelerate the waste decomposition process [48]. This trend aligns with the broader shift toward smart agriculture, where artificial intelligence and IoT optimise resource use and increase agricultural productivity [24].

Figure 11 depicts the thematic evolution of keywords across four time slices: 2016-2018, 2019-2020, 2021-2022, and 2023-2024. In the first slice from 2016 to 2018, keywords such as "organic wastes", "biomass", and "IoT" emerged as prominently reflected in the initial exploration of IoT applications in agricultural waste management. This early focus was primarily on integrating IoT systems to monitor waste decomposition and biomass production [45]. The keyword "biomass" highlights the significance of organic waste as a primary focus area driven by the increasing demand to utilise waste materials for energy production and composting [49]. In the second time slice (2019-2020), “IoT” continues to be a dominant keyword, but new terms such as “efficiency”, “renewable energy resources”, and “agricultural robots” emerge. This shift signifies a deeper focus on enhancing the efficiency of IoT-based systems in agriculture with particular emphasis on energy optimisation and automation.

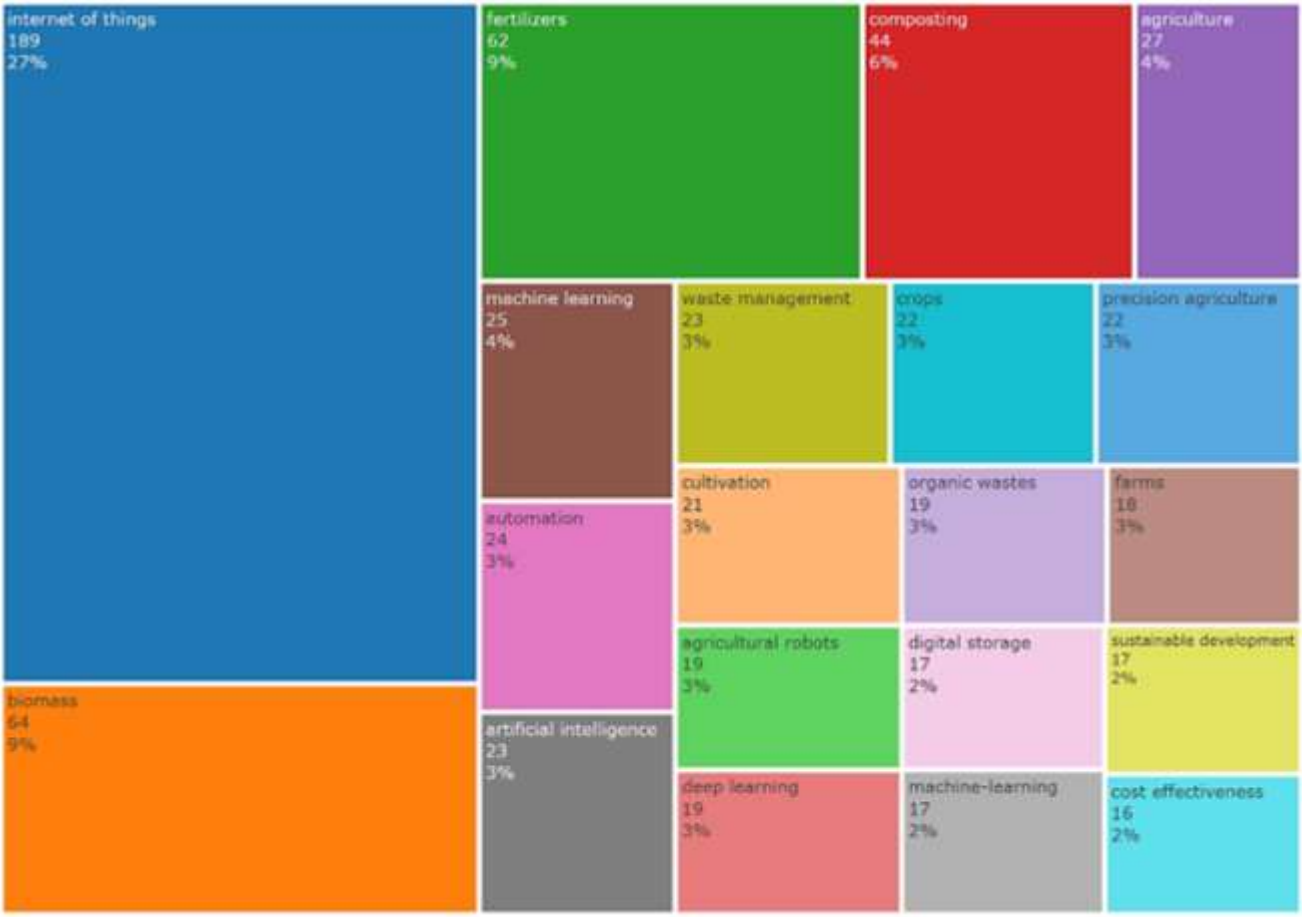

Fig. 10. Treemap diagram of the 20 most important keywords in the research area

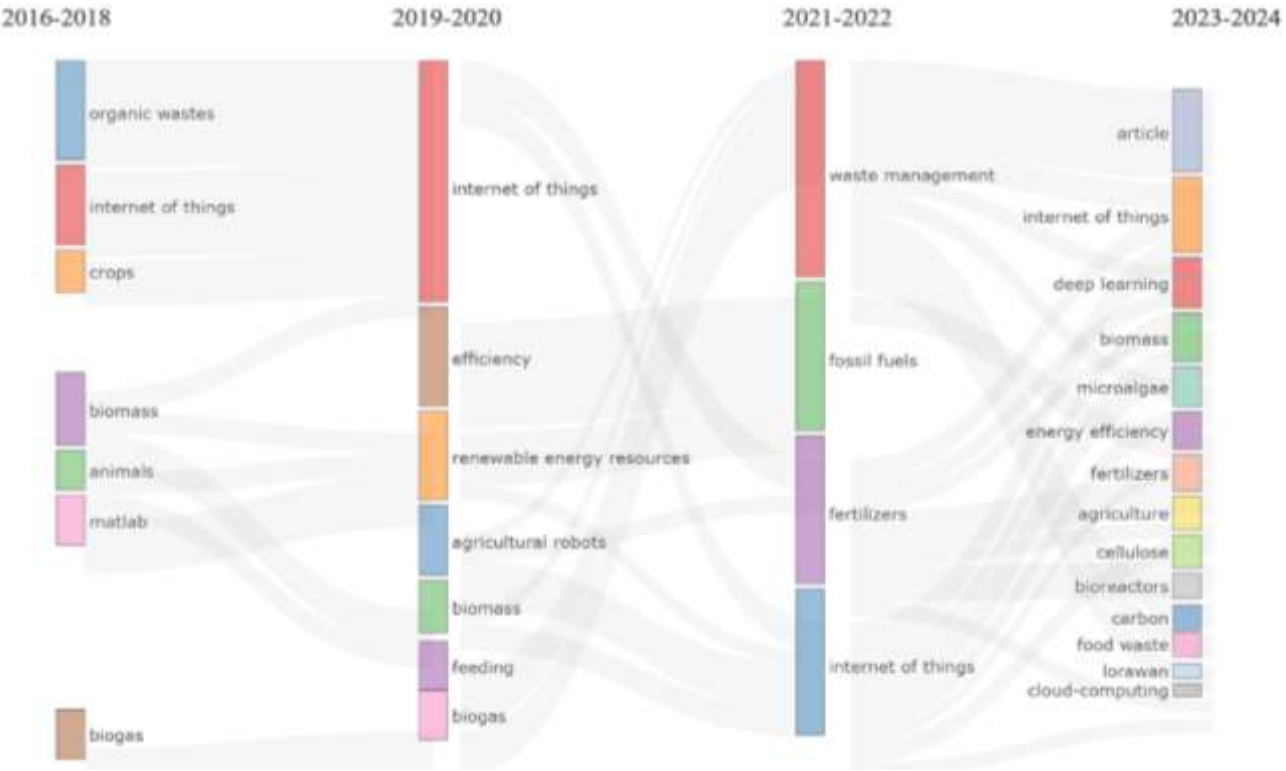

Fig. 11. Thematic evolution of the keywords based on four-time slice (Slice 1: 2016-2018, Slice 2: 2019-2020, Slice 3: 2021-2022, and Slice 3: 2023-2024)

In the third time slice (2021-2022), keywords like “waste management” and “fossil fuels” become more prominent, indicating a growing concern about the environmental impact of agricultural practices. During this period, research focused on reducing fossil fuel dependency by adopting renewable energy resources, such as solar power, to operate IoT systems. This trend aligns with global efforts to promote sustainable farming practices that minimise carbon footprints [50]. The final time slice (2023-2024) highlights emerging technologies such as “deep learning”, “biomass”, and “microalgae”. The appearance of deep learning indicates the increasing use of advanced artificial intelligence techniques to improve the precision and efficiency of IoT-based agricultural systems. This includes predicting optimal composting conditions and automating waste management processes [30]. Additionally, the focus on microalgae suggests a new area of research that explores its potential in waste treatment and energy production within agricultural systems [51,52].

4. Conclusions

This current study provides a comprehensive bibliometric analysis of the integration of composting and the Internet of Things (IoT) from 2016 to 2024. It highlights key trends along with leading authors, institutions, and countries in this rapidly evolving field. The analysis identifies India, China, and Malaysia as leading research hubs contributing significantly to advancements in smart waste management, environmental sustainability, and agricultural optimisation, mainly through integrating IoT technologies. The keyword analysis and thematic evolution highlight the increasing importance of biomass monitoring, artificial intelligent-driven systems, and renewable energy in composting practices. The role of IoT in real-time monitoring and automation has become a key factor in improving the efficiency and scalability of composting operations. It holds the potential to transform global waste management and agricultural practices. The co-occurrence network analysis reveals a dual emphasis on IoT-based monitoring systems and smart waste management. Therefore, it reflects IoT's expanding role in optimising composting processes and enhancing the efficiency of organic waste management.

One limitation of this study is reliance solely on the Scopus database. While Scopus is comprehensive, it may exclude relevant publications on composting and IoT that are available in other databases such as Web of Science or Google Scholar. Additionally, the bibliometric analysis includes publications only up to 2024, which may result in the exclusion of recent studies or research developments from the later months of 2024. Future research could build on this bibliometric analysis by including additional databases to provide a more comprehensive view of the publications. Further exploration of the practical applications of IoT-based composting technologies in various agricultural sectors is also recommended. Moreover, the integration of deep learning and machine learning into IoT systems for predictive analysis in composting remains a promising area for further investigation. Cross-disciplinary collaborations, especially involving environmental science, artificial intelligence, and renewable energy, will be critical for advancing research in this domain and developing more efficient and scalable composting systems globally.

Acknowledgement

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