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Internet of Things (IoT) and the Environmental Sustainability: A Literature Review and Recommendations for Future Research

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ABSTRACT

As the Internet of Things (IoT) surges forward, intersecting with an urgent demand for environmental sustainability (ES), digital technologies emerge as potent orchestrators of systemic transformation. Employing a subtle blend of bibliometric-systematic literature review (B-SLR) and qualitative insights, this research investigates IoT's multifaceted roles—spanning smart urban systems, precision agriculture, and intelligent waste management. Anchored theoretically in the multi-level perspective (MLP), the analysis illuminates how groundbreaking niche experiments infiltrate entrenched regimes, propelled by strategic digitalization pathways and enriched by open innovation's collaborative dynamism. Yet, complexities arise: interoperability hurdles, persistent standardization bottlenecks, and intricate security dilemmas remain. Addressing these demands requires robust engagement across diverse actors, turning isolated innovations into large-scale, systemic realities. Ultimately, the study stresses that navigating this intricate interplay between digitalization and open innovation is indispensable for catalyzing genuine sustainability transitions.

1 | Introduction

Sustainability is a comprehensive concept that aims to meet the needs of the present without compromising the ability of future generations to fulfill their own needs, as articulated in Brundtland (1987). It encompasses various dimensions, including economic, social, and environmental aspects (Elkington and Rowlands 1999). Among these, environmental sustainability (ES) is paramount as it directly addresses critical global challenges such as climate change, pollution, and waste management (Wu et al. 2022). The increasing environmental concerns have led to a concerted effort to research and develop innovative solutions that mitigate negative environmental impacts among governments, scientific communities, and organizations (National Research Council 1996). In this regard, many scholars have addressed these three critical aspects. For instance, Adanma and Ogunbiyi (2024) highlight the role of policy frameworks and international agreements in fostering sustainable practices. Hekkert and Negro (2009) emphasize the importance of scientific research in understanding environmental changes and developing technological solutions. Zameer et al. (2021) discuss how corporate responsibility and consumer awareness are driving businesses to adopt greener practices. These efforts are comprehensively reflected in the growing body of research dedicated to exploring and implementing environmentally sustainable strategies (Elliot 2013).

In the effort to promote and enhance ES, digitalization is emerging as an increasingly important component (Mondejar et al. 2021). Recognized by the United Nations as essential for achieving sustainable development goals (SDGs), digital transformation encompasses a range of technologies that can enhance sustainability efforts (UNEP 2021). Even the European Commission underscored the simultaneous importance of

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sustainability and digitalization in shaping contemporary policies by introducing the concept of "twin transitions," highlighting how digital technologies and innovation are central for driving ES, while, at the same time, ES influences the development of digital technologies (European Commission 2020). With regard to the most influential technologies in promoting ES, technologies such as IoT, Big Data, advanced analytics, and artificial intelligence are increasingly seen as enablers of sustainable practices (Agrawal et al. 2022). Indeed, these technologies can contribute to improving resource efficiency, reducing waste, and facilitating the development of smart solutions for environmental challenges such as climate change, air and water pollution, and soil degradation (Cavalieri et al. 2022).

Among these technologies, IoT stands out as a foundational technology for introducing ES benefits, and numerous scholars have studied it extensively (Marchet et al. 2014; Holzmann and Gregori 2023). Specifically, IoT is defined as a network of interconnected physical objects that communicate with each other and other internet-enabled technologies that collect and exchange data to drive smart solutions (Hounsell et al. 2009; Ramos et al. 2008). Scholars have analyzed the benefits of IoT toward ES from various perspectives, demonstrating its importance in multiple applications such as smart cities, environmental monitoring, energy management, and intelligent waste management. For instance, the application of IoT in creating smart cities has been extensively documented, and several scholars have shown how IoT enables real-time data collection and analysis through network sensors, thereby improving urban infrastructure and services (Zanella et al. 2014; Plageras et al. 2018). Also, Siemens' research on City Air Management solutions demonstrates IoT's capability to predict air quality, aiding in pollution control efforts (Siemens 2020). Other studies by Ja Ajith et al. (2020) highlight IoT's ability to provide real-time data on air and water quality, aiding in timely intervention and pollution management. In the realm of energy management, IoT facilitates the seamless integration of renewable energy sources and optimizes energy distribution; therefore, it contributes to reduced carbon emissions and enhanced energy efficiency, as evidenced by the works of Chen and Jin (2012) and Yang et al. (2020).

Environmental monitoring represents another critical area where IoT has shown significant potential (Kosovic et al. 2020). For instance, New York Waterway ferries utilize IoT to aggregate data from connected sensors, supporting intelligent public transportation systems and reducing environmental impact (Hounsell et al. 2009). Furthermore, the field of intelligent waste management is enhanced by IoT technologies. IoT-enabled smart bins equipped with sensors can optimize waste collection routes, reducing fuel consumption and lowering greenhouse gas emissions (Mousavi et al. 2023). From a practical point of view, the work of Bigbelly (2020) in public spaces exemplifies how IoT can revolutionize waste and recycling solutions, promoting efficient resource use and minimizing waste.

Although scholars increasingly acknowledge the profound potential of merging digital technologies with ES, research often remains fragmented—treating digitalization and sustainability as distinct, parallel trajectories (Costa 2024). This compartmentalization, evident across various studies (Beier et al. 2020; Bibri 2020; Ejsmont et al. 2020; Grybauskas et al. 2022; Piscicelli 2023; Upadhyay et al. 2021), inadvertently obscures the intricate web of interactions and cumulative impacts emerging at their intersection. Addressing this gap demands a more integrative theoretical lens—one capable not only of unpacking IoT's transformative potential for sustainability but also embedding it firmly within the broader, multifaceted dynamics characterizing socio-technical transitions.

To address this research gap, our study adopts a Bibliometric-Systematic Literature Review (B-SLR) approach, analyzing 160 peer-reviewed papers from the Scopus database, guided accurately by the methodology articulated in Marzi et al. (2025). This analytical approach illuminates a dynamic collection of research patterns, reveals complexities, and discloses significant trajectories concerning IoT's contributions to ES. Integrating the theoretical robustness of the multi-level perspective (MLP) (Geels 2002), our analysis captures the evolutionary journey of IoT innovations, from their fragile origin within experimental niches to their gradual embedding within entrenched socio-technical regimes. Our analysis argues that the widespread diffusion of IoT demands a profound recalibration of socio-technical structures, enacted through strategic and digitally enabled collaboration. Thus, this twin transition, linking digitalization with ES, emerges not as parallel pursuits but as mutually constitutive, interconnected paths toward systemic transformation.

Our review advances the scholarly conversation by offering an integrative, in-depth examination of IoT applications within the realm of ES, exposing prevailing research trends, overlooked complexities, and prospective research frontiers. The analysis uncovers IoT's fundamental, yet diverse, contributions—spanning smart energy management, intelligent waste solutions, environmental monitoring, precision agriculture, circular economy strategies, and smart urban ecosystems. In doing so, we articulate a compelling case for a future research agenda that positions digitalization and open innovation as catalytic forces propelling systemic shifts toward genuine ES. Moreover, the review identifies significant gaps, such as the need for standardization and interoperability of IoT systems, and the need to develop IoT management capabilities focused on ES. Therefore, this study not only contributes to the debate by expanding the current understanding but also provides valuable insights for future policies and practical guidelines for professionals and policymakers interested in leveraging IoT to advance ES goals.

Following this introductory section, the paper is structured as follows: Section 1 explores the theoretical framework, delving into the foundational concepts of IoT and ES and analyzing their intersections within the broader context of digital transformation, twin transition, and socio-technical shifts. Section 2 outlines the methodology, detailing the mixed-method approach employed for the bibliometric and content analysis, as well as the data selection process from the Scopus database. Section 3 presents the results of the analysis, providing a detailed description of the bibliometric data and a thematic exploration of key research trends, challenges, and gaps in the application of IoT to ES. In Section 4, the results are critically discussed, highlighting the practical applications of IoT in key sectors such as smart cities, precision agriculture, and the circular economy, while also offering insights to bridge the identified gaps and guide future research directions. Finally, Section 5 concludes the study by summarizing its main contributions, acknowledging its limitations, and proposing implications for future research and policymaking to leverage IoT as a tool for promoting ES.

2 | Theoretical Background

Over the past decade, IoT has established itself as a cornerstone of digital transformation and twin transition, which combines ecological and technological imperatives in one convergent paradigm (European Commission 2020). More than a buzzword, IoT represents a complex and evolving technological architecture that enables the interaction of physical objects with digital networks, allowing them to collect, transmit, and act upon data autonomously (Jia et al. 2012). At its essence, this paradigm fosters a form of ambient intelligence, where previously inert devices become agents of computational awareness.

Yet, despite its diffusion, IoT eludes a stable, universally accepted definition. As Vermesan et al. (2022) argue, its multifaceted applications—ranging from agriculture to aerospace—resist reduction to a singular conceptual core. The term itself, coined by Kevin Ashton in 1999 at MIT's Auto-ID Center, originally envisioned objects endowed with sensor-based "senses" akin to human faculties: seeing, hearing, touching, acting. That vision remains foundational, yet insufficient to encapsulate the vast networked intelligence IoT has become. The International Telecommunication Union (ITU-T), for example, frames IoT as a foundational infrastructure of the Information Society—a global network interlinking physical and virtual entities via interoperable technologies (Mazlumi and Kermani 2022).

Historically, one of the earliest demonstrations of IoT's potential was, quite appropriately, contemporary: a toaster, controlled via the internet in the 1990s (Welbourne et al. 2009). From such simple origins, IoT has evolved into a sprawling ecosystem—its growth shadowing, and perhaps even shaping, the parallel evolution of the Internet itself (Kamble et al. 2019).

To contextualize this evolution, some scholars describe IoT as a late phase in the Internet's development—one where physical objects become both participants and interlocutors in the digital dialogue (Tan and Wang 2010). But such a view is reductive. The contemporary IoT landscape extends well beyond simple object-to-network communication, permeating industrial automation, smart agriculture, healthcare, urban planning, and beyond (Mu and Antwi-Afari 2024). While early iterations of IoT focused on RFID and sensor-based connectivity—technologies adept at object identification and real-time monitoring without direct visual contact (Dominikus et al. 2010)—today's iterations are enmeshed in layered infrastructures and service-based architectures.

Indeed, modern IoT devices have become ubiquitous in everyday life, rendering once-ordinary items "smart." This transformation redefines user-object relationships and introduces new modes of autonomy into the built environment (Deguchi et al. 2020). The shift is driven, in large part, by IoT's capacity to harvest and analyze massive volumes of real-time data across sensor networks, communication protocols, and cloud platforms (Botta et al. 2016). Farooq and Akram (2021) underscore that such integrations imbue objects with the ability to perceive environmental conditions and adapt behavior accordingly—transforming objects from tools into quasi-agents. Interoperability is decisive here. The success of IoT hinges on the seamless coordination among disparate devices, protocols, and platforms (Shaikh et al. 2015). In technical terms, this entails the construction of a universal, scalable network infrastructure capable of managing the sheer diversity of connected things. Notably, the adoption of IPv6 protocols is a critical enabler, ensuring addressability and scalability (Al-Fuqaha et al. 2015). Meanwhile, the Service-Oriented Architecture (SOA) model underpins the logical structuring of IoT: from data collection at the sensing layer to communication across the network layer, processing at the service layer, and ultimately, user interaction via the interface layer (Li et al. 2015; Del Sarto et al. 2022).

Nonetheless, the path toward widespread adoption is fraught with institutional, technical, and economic impediments. Regulatory ambiguity, technological fragmentation, and the absence of unified standards remain persistent barriers (Kamble et al. 2019). Standardization—especially in communication protocols—is not merely a technical challenge but a geopolitical one, requiring international consensus to ensure equitable and secure deployments (Bandyopadhyay et al. 2011; Pang et al. 2015). For SMEs in particular, high infrastructure costs and delayed return on investment (ROI) timelines represent nontrivial adoption hurdles (Luthra et al. 2018). And perhaps most critically, security and privacy concerns loom large: the immense volume of sensitive data circulating within IoT ecosystems makes them fertile ground for cyber vulnerabilities (Abomhara and Køien 2015). Mitigating these risks calls for robust encryption protocols, adaptive access controls, and secure device authentication (Sicari et al. 2020).

Yet beyond its technical prowess, IoT stands at the nexus of technological advancement and ecological stewardship. Its capacity for granular, real-time environmental monitoring positions it as a linchpin in the pursuit of ES. Cabezas et al. (2004) conceptualize ES as the systemic balance between human activity and natural ecosystems—an equilibrium wherein economic growth and social welfare operate in concert with ecological integrity. Flint and Flint (2013) elaborate on this triadic model, emphasizing the interdependence of prosperity, equity, and environmental protection.

Chapin III et al. (2009) remind us that ES demands regenerative use of natural capital. Within this framework, IoT emerges as both a diagnostic and interventional tool. In precision agriculture, for instance, real-time sensor data on soil moisture, crop health, and weather conditions allows for targeted irrigation and fertilization, reducing both waste and ecological runoff (Zhang et al. 2018). In waste management, smart bins equipped with IoT sensors optimize collection routes, thereby lowering CO_2 emissions (Anagnostopoulos et al. 2017). The circular economy, too, benefits: IoT enables lifecycle tracking of materials, facilitating reuse, recycling, and remanufacturing processes (Prendeville et al. 2014; Brandín and Abrishami 2021; Zardo et al. 2025). In Smart Cities, real-time monitoring of transportation and energy networks enables both energy savings and a reduced environmental footprint (Lv and Shang 2023; Bibri 2020).

The real breakthrough, however, lies in the convergence of IoT with other emergent technologies—AI, Big Data analytics, blockchain. Such hybridized systems amplify the capability to manage complexity, anticipate disruption, and enact sustainable change (López-Vargas et al. 2020; Nižetić et al. 2020).

Therefore, considering IoT's transformative potential across sectors—particularly its role in enabling environmentally sustainable practices through data-driven automation and interconnectivity—it becomes increasingly clear that technological deployment alone does not account for the complex dynamics of socio-technical change (Cardinali and De Giovanni 2022). Equally critical is the broader institutional, infrastructural, and societal context within which such technologies emerge, diffuse, and stabilize (Cambra-Fierro et al. 2024). To capture these dynamics, our literature review is anchored in the MLP on socio-technical transitions (Geels 2002), a theoretically grounded framework for analyzing the co-evolution of technologies, institutions, and societal practices over time. MLP conceptualizes innovation as the outcome of interactions across three analytical levels: niches (protected spaces for emerging innovations), regimes (dominant structures and practices), and the landscape (macroscopic trends and exogenous pressures). This framework is particularly suited to analyze technologies like IoT, whose development cannot be fully understood without considering the institutional rigidities, political incentives, and cultural discourses that accompany their material diffusion. While many IoT applications have already permeated regime-level systems (e.g., industrial automation, smart mobility), others remain confined to niche-level experimentation, such as blockchain-IoT pilots or decentralized energy management in rural areas. Simultaneously, landscape-level pressures—including climate change, post-pandemic digital acceleration, and the European Green Deal—act as exogenous forces catalyzing or constraining these trajectories (European Commission 2020). The twin transition conceptualizes digitalization and ecological transformation as co-evolving processes, where technologies such as IoT are not neutral tools but directional enablers of systemic change, embedded with normative assumptions about what constitutes sustainable futures (Schot and Steinmueller 2018). This macro-perspective prompts an evaluation of the ecological intentionality embedded within technological applications across domains such as energy, mobility, and agriculture (Ghobakhloo et al. 2023).

By applying MLP to our bibliometric-systematic review (Marzi et al. 2025), we analyzed how scholarly contributions are distributed across niche innovations, regime adaptations, and landscape influences—revealing not only the technological directions of IoT, but also the socio-political and institutional mechanisms that support or constrain its contribution to sustainability transitions. In doing so, our review uncovers the deeper socio-technical mechanisms—alignment, resistance, stabilization—through which digital and ecological transformations interact.

3 | Methodology

Our analysis, conducted in July 2024, unfolded through a meticulous mixed-methods approach, seamlessly weaving together bibliometric scrutiny and qualitative depth. To ensure methodological rigor, we adhered strictly to the 10-step B-SLR framework proposed by Marzi et al. (2025), a process designed not merely to map academic discourse but to distill its very essence. As a first step, we focused on identifying a distinct theoretical gap within the literature concerning the intersection of the Internet of Things (IoT) and ES. While both topics have independently attracted considerable academic interest, there remains a lack of studies that systematically integrate IoT with ES (Costa 2024). This gap called for a research question that would not only capture the primary contributions of IoT to ES but also address the challenges related to its implementation. Given this objective, we formulated a comprehensive search strategy designed to capture the full breadth of existing research in these domains. To ensure a robust and exhaustive search, we crafted a search query incorporating a wide range of terminologies related to both IoT and ES. This approach followed an inductive methodology, wherein we initially experimented with multiple query variations, manually reviewed the results, and refined the selection criteria to enhance precision. Since IoT encompasses an extensive array of smart technologies and connected devices, it was essential to account for its multifaceted applications, as emphasized by Nižetić et al. (2020). Similarly, ES as a field of study required the identification of numerous keywords that would comprehensively capture its research focus and objectives, following the recommendations of Dong and Hauschild (2017). Our final search query, which included terms spanning environmental monitoring, energy efficiency, smart cities, circular economy, and connected devices, leveraged a comprehensive set of key definitions in the field of inquiry (Ardito et al. 2018; Cecere et al. 2014; Balasubramanian and Shukla 2020; Sajjad et al. 2020) and was applied across abstracts, author keywords, and titles, ensuring comprehensive coverage.

(**QUERY:** TS "environmental sustainability" OR "energy efficienc*" OR "environmental monitoring" OR "emission reduction*" OR "waste management" OR "smart cit*" OR "precision agriculture" OR "air pollution" OR "energy saving*" OR "renewable energ*" OR "circular economy" OR "resource conservation" OR "green technolog*" OR "ecological footprint*" OR "environmental management system*" OR "air qualit*" OR "water resource management" OR "smart recycling" OR "environmental sensor*" OR "sustainable practice*").

AND ("Internet of Things" OR IoT OR "smart device*" OR "connected device*" OR "wireless sensor network*" OR "smart sensor*" OR "machine-to-machine communication" OR "M2M" OR "edge computing").

Here, "TS" refers to searches conducted across abstracts, author keywords, and titles.

The Scopus database emerged as the optimal engine for our bibliometric investigation, renowned for its extensive multidisciplinary coverage and methodological reliability in bibliometric analytics, particularly within Business and Management research (Faruk et al. 2021; Herrera-Franco et al. 2020; Khudzari et al. 2018). The initial extraction yielded a staggering 66,424 publications—a corpus too vast for targeted insight. By imposing a temporal filter, restricting our scope to works published between 2015 and 2024, we refined the dataset to 53,370 documents. From there, we drilled further into Business and Management classifications within Scopus, recognizing that sustainability's practical adoption hinges on economic, organizational, and managerial considerations. This strategic refinement yielded 1729 articles, offering a vantage point to explore how IoT technologies are operationalized within corporate and policy frameworks. From this corpus, the reducing began. Duplicates, non-relevant studies, and peripheral sources—conference proceedings, book chapters, and industry reports—were systematically eliminated, bringing the dataset to 800 articles. A finer filter was then applied, where metadata—titles, abstracts, keywords—were scrutinized to isolate only those works essential to our research inquiry. To elevate methodological rigor, we imposed an additional layer of selectivity: only articles published in Q1 journals were retained, reducing the final dataset to 160 meticulously chosen studies. This decision, far from arbitrary, was driven by a commitment to analytical precision and scholarly excellence. As underscored by Garfield (1970) Q1 journals represent the apex of academic inquiry, defined by superior impact factors and methodological stringency. Roppelt et al. (2024) further reinforces this, arguing that prioritizing Q1 journals ensures that only the most methodologically rigorous, peer-reviewed contributions inform the analysis. Mañana-Rodríguez (2015) and Jacsó (2010) echo this sentiment, positioning Q1 sources as the gold standard for systematic reviews, given their substantial contributions to shaping contemporary research landscapes. The final dataset was exported into a format compatible with Bibliometrix, an advanced R package designed for high-precision bibliometric analysis (Aria and Cuccurullo 2017). Unlike traditional literature reviews, which often lean on pre-coded thematic structures or narrative heuristics—both prone to researcher bias—Bibliometrix provided an empirical, quantitatively driven lens. Through its analytical framework, we extracted key citation metrics, mapped co-authorship networks, analyzed keyword co-occurrence frequencies, and deployed cluster analyses to identify emergent research themes. Each document was evaluated not merely for its citation impact but for its position within the intellectual ecosystem—its relational gravity within the field. To ensure conceptual clarity and coherence, we adjusted resolution parameters and cluster granularity, isolating dominant research threads while preserving the integrity of niche perspectives. Once thematic clusters were delineated, a secondary round of analysis commenced: a qualitative investigation into each cluster. We assessed their theoretical foundations, internal cohesion, and relevance to the overarching research question. Documents within each cluster were then ranked based on normalized citation scores and thematic centrality, allowing for the identification of a representative subsample that would undergo further qualitative synthesis. Building upon the bibliometric mapping, we transitioned into the systematic qualitative review. This phase was an analytical confrontation with the literature, comparing methodologies, identifying theoretical frictions, and exposing research blind spots. We interrogated the practical viability of IoT as an enabler of ES, dissecting real-world applications against theoretical claims. The review surfaced a complex interaction of technological potential and systemic constraints—issues of interoperability, regulatory inertia, and the challenge of aligning IoT's capabilities with sustainable governance structures. By synthesizing bibliometric insights with qualitative rigor, we constructed a comprehensive theoretical framework, not only mapping the state of knowledge but charting future research trajectories and managerial implications. The fusion of quantitative bibliometric precision with qualitative theoretical synthesis produced a research roadmap, shedding light on both the transformative possibilities and the challenging barriers that define IoT's role in ES. Figure 1 provides a detailed visualization of the article selection process undertaken in this review based on the 10 steps of the B-SLR method.

4 | Results

4.1 | Descriptive Analysis

Table 1 summarizes general quantitative data from the selected dataset. The 160 papers included have an average citation count of 79.8 from 2015 to 2024. They were published across 39 different journals and authored by 615 contributors, with an average of 4.34 co-authors per document. Among these, there are only 4 documents authored by a single individual, and the rate of international co-authorship per document stands at 50.62%.

Figure 2 illustrates the annual scientific output on the topic of IoT, which demonstrates a significant increase with an annual growth rate of 17.77%. This growth highlights the academic community's expanding interest in this field. However, while scholarly attention surged notably from 2015, reaching a peak in 2021, Figure 2 reveals a subsequent decline in IoT research output. This downturn coincides with the rising prominence of artificial intelligence as a research focus, which may have influenced the negative trend observed in the following year. This shift underscores the dynamic nature of research trends and the impact of emerging fields on established areas of inquiry (Figure 6, later in this review, analyzes this phenomenon).

At the country level, the analysis reveals that the study of IoT is a global focus of scholarly interest. As shown in Figure 3, China and India emerge as the leading contributors, underscoring their dominant role in the development of smart products and sensors. Indeed, these countries have consistently topped many rankings in the field of innovation management, particularly in areas related to digital transformation. However, it is equally important to recognize the significant contributions from other countries, such as the USA, UK, Italy, and Spain, which have a strong presence in this research domain. This distribution is consistent with the technological advancements and innovation-driven economies of these nations. Moreover, there is an increasing engagement from countries like South Korea and Pakistan, reflecting a more widespread interest in IoT research, which is closely tied to the production of technological devices in the case of South Korea, but there is optimism regarding scholars' sensitivity to this issue, particularly given the encouraging interest shown by academics in Pakistan, as highlighted in Table 2. Instead, regarding the output at the level of academic institutions, Northwestern Polytechnical University in China stands out as the most productive institution, having published 16 articles on the subject, confirming that China is the leading country in addressing this phenomenon. However, it is not followed by Indian universities but, conversely, by the University of Cambridge in the UK and the University of Split in Croatia, each

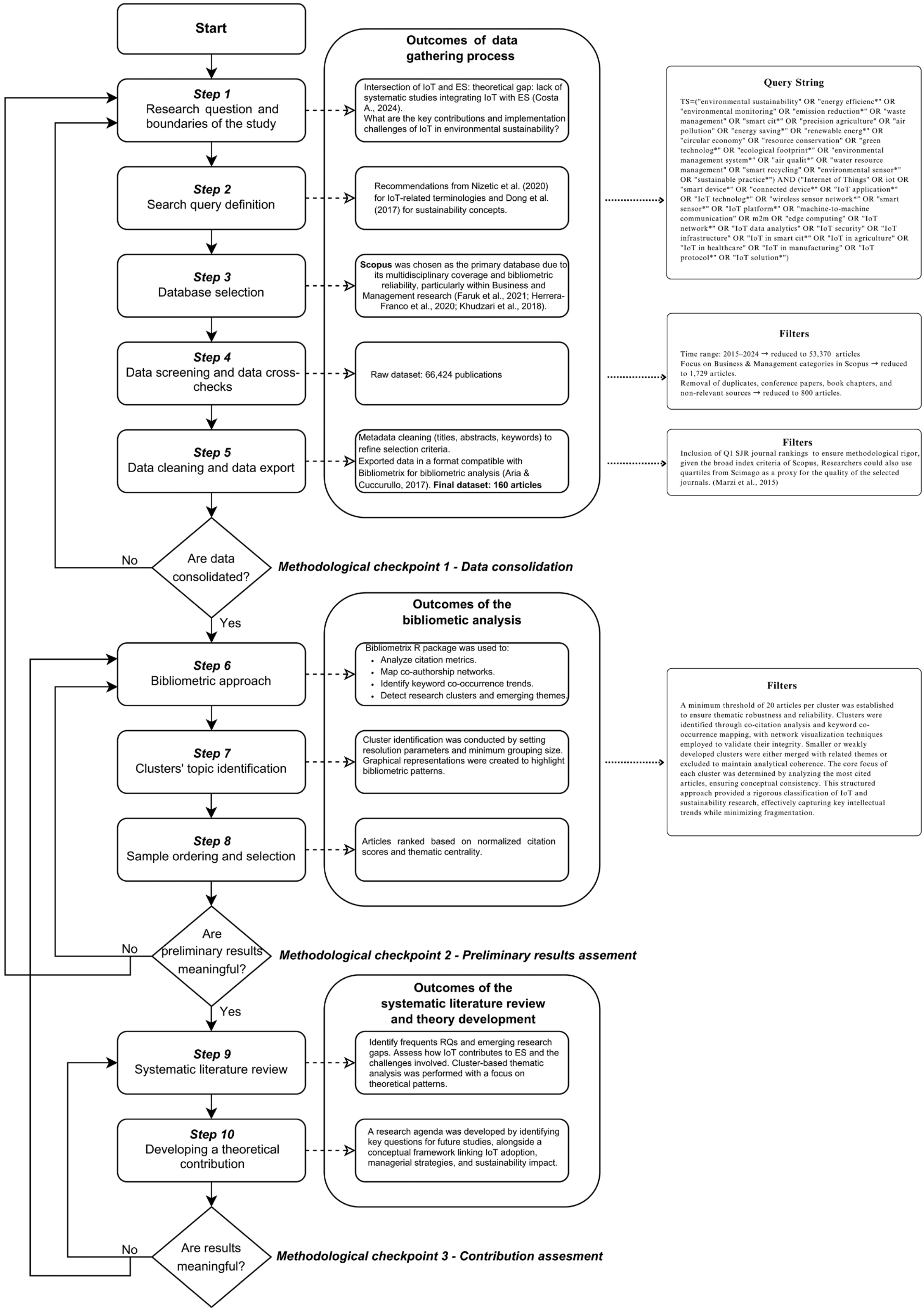

FIGURE 1 | Research design.

with 11 published articles, signifying that European universities are increasingly addressing this topic.

The analysis of the most productive sources is depicted in Figure 4, which lists the 15 most prolific journals in the sample. There is a significant disparity between the top journal and the rest in terms of article volume. Indeed, Journal of Cleaner Production is at the forefront with 69 articles, clear evidence that sustainability journals are increasingly addressing the strong connection between sustainability and digital technologies, as well as the opportunities that can arise from this relationship. Followed by Cities, which has published only 13 documents. However, despite this discrepancy between the first and second journal, it is evident that the theme of Smart Cities stands out prominently when discussing IoT and ES, since the journal Cities plays a significant role in advancing research within the context of urban development. Overall, the ranking of the sources illustrates that the topic of IoT and ES is covered across various domains, evidencing its interdisciplinary nature. Journals such as IEEE Transactions on Engineering Management, Business Strategy and the Environment, Technology in Society, and Journal of Global Information Management focus on digital technologies as well as the managerial skills and strategies necessary for these technologies to effectively promote sustainability. Conversely, more specialized journals like Big Data Research, Industrial Management and Data Systems, and International Journal of Precision Engineering address specific aspects of IoT, closely tied to technological developments and barriers. This diversity of sources indicates that digital transformation is not merely a technological advancement but also a multidimensional phenomenon shaped by various drivers, including technology management, innovation management, and computing engineering. This interdisciplinary coverage reinforces the broad applicability and the strategic importance of IoT in addressing environmental challenges, as its implementation touches on diverse aspects of business strategy, data management, and technological innovation. Such a broad reach suggests that its impact requires collaborative efforts across fields to fully harness its benefits.

TABLE 1 | Main informations about data, authors and collaboration between authors.

Description	Results
Main informations about data	
Timespan	2015–2024
Sources (Journals, books, etc.)	39
Documents	160
Annual growth rate %	29.86%
Document average age	3.16
Average citations per document	79.8
References	11.439
Authors	
No. of authors	615
Authors keywords	632
Authors of single-authored documents	4
Authors collaboration	
Co-authored documents	4.34
International co-authorships %	50.

4.2 | Content Analysis

To examine the main avenues of current research as well as pinpoint research gaps and potential future directions on IoT and ES, this study incorporates content analysis. Starting by examining the yearly trend topics, it turns out to be evident that the focus on various technologies spans different timeframes. For instance, themes based on artificial intelligence, which represent the most recent technological developments, reached their zenith during 2023. Conversely, those related to manufacture and electric power transmission networks primarily emerged up until 2018. In particular, there has been significant attention toward IoT during 2021. This examination further underscores

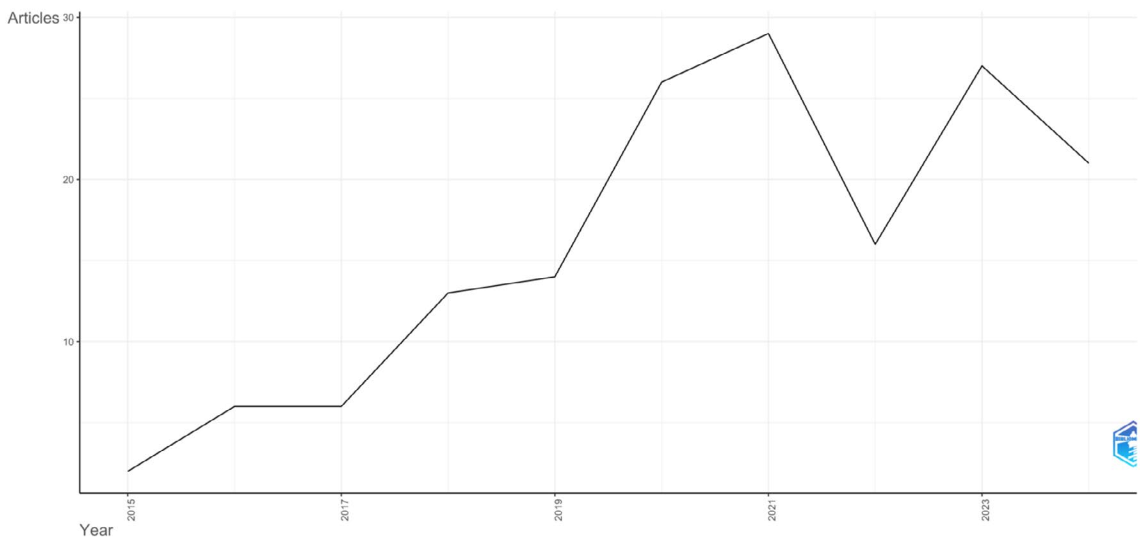

FIGURE 2 | Annual scientific production of the selected articles.

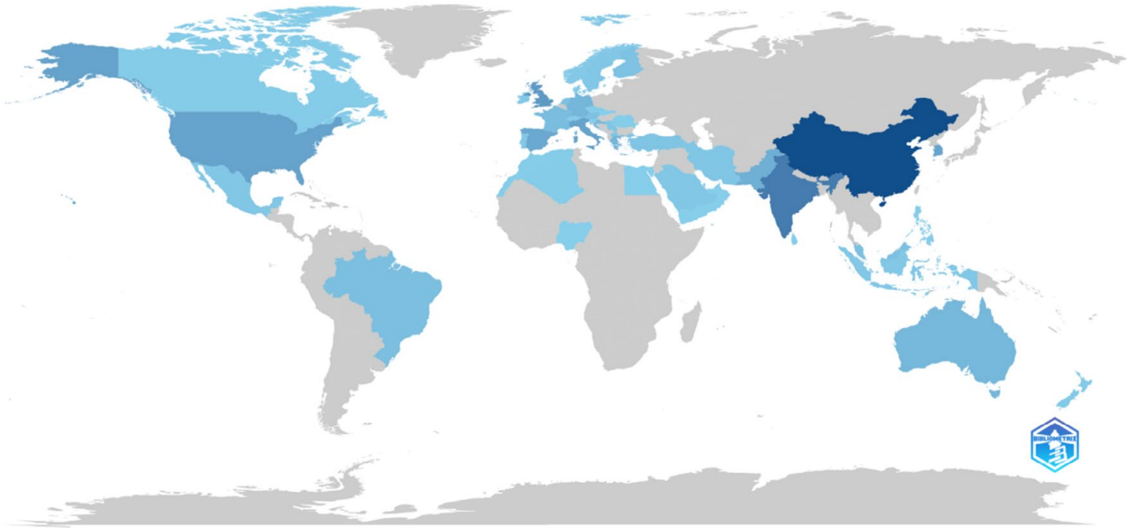

FIGURE 3 | Country scientific production.

TABLE 2 | The top 20 productive countries and citations per country.

Country	Total documents	Average article citations
China	120	84.1
India	75	29.9
UK	47	102.4
USA	39	119.7
Italy	38	57.2
South Korea	37	43
Spain	33	76.2
Pakistan	27	19.8
Germany	22	56.8
Greece	22	42.8
Australia	20	170.7
Croatia	18	141.2
France	16	35
Brazil	14	67.6
Malaysia	12	447
Austria	11	94
Finland	11	101
Netherlands	11	17.2
North Macedonia	9	51

the interdisciplinary character of the topic, which simultaneously concentrates on specific technological advancements and the broader industrial revolution. Figure 5 showcases the top 16 most frequent trend topics per year.

The evolving trends in Figure 5 underscore the dynamic forces shaping academic interests over time. Initially, research in these areas was heavily centered around "manufacturing," coinciding with the development of topics like "wireless sensor networks" and "energy utilization" (Anand and Rr 2018). This pattern reflects an early focus on linking industrial and energy dimensions, particularly in contexts where energy optimization and sensor networks played a critical role in advancing manufacturing processes (Han et al. 2019). As time progressed, themes such as "energy efficiency" and "sustainable development" began to attract significant academic attention. These shifts marked the beginning of broader discussions on sustainability and energy conservation, foreshadowing the dominant trends of 2020 and beyond. Notably, topics like the "Internet of Things" (IoT) and "Smart Cities" have maintained a continuous presence from 2017 to 2024, demonstrating a sustained scholarly interest. Their extended relevance suggests these areas are key enablers in addressing ES and urban development challenges. Recently, this focus has broadened to include cutting-edge topics such as "blockchain" and "waste management," contributing to a more holistic understanding of sustainability. The incorporation of these newer domains signals academia's increasing emphasis on systemic solutions to environmental challenges. Moreover, the integration of "artificial intelligence," "decision making," and "waste management" (Wu et al. 2022; Chiang 2024) into these discussions demonstrates the evolution toward more interdisciplinary approaches. These trends indicate that the academic community is recognizing the strategic importance of combining IoT with ES practices, offering new pathways for innovation and development. The continuing exploration of "sustainability," "energy efficiency," and "smart cities" underscores the critical role these concepts play in shaping future research and practical applications.

4.3 | Thematic Analysis

The conceptual structure presented in Figure 6 effectively showcases the development of the main trends within the analyzed document set, organized into a two-by-two matrix depicting different thematic categories. This matrix is particularly useful for understanding how various themes are positioned in terms of

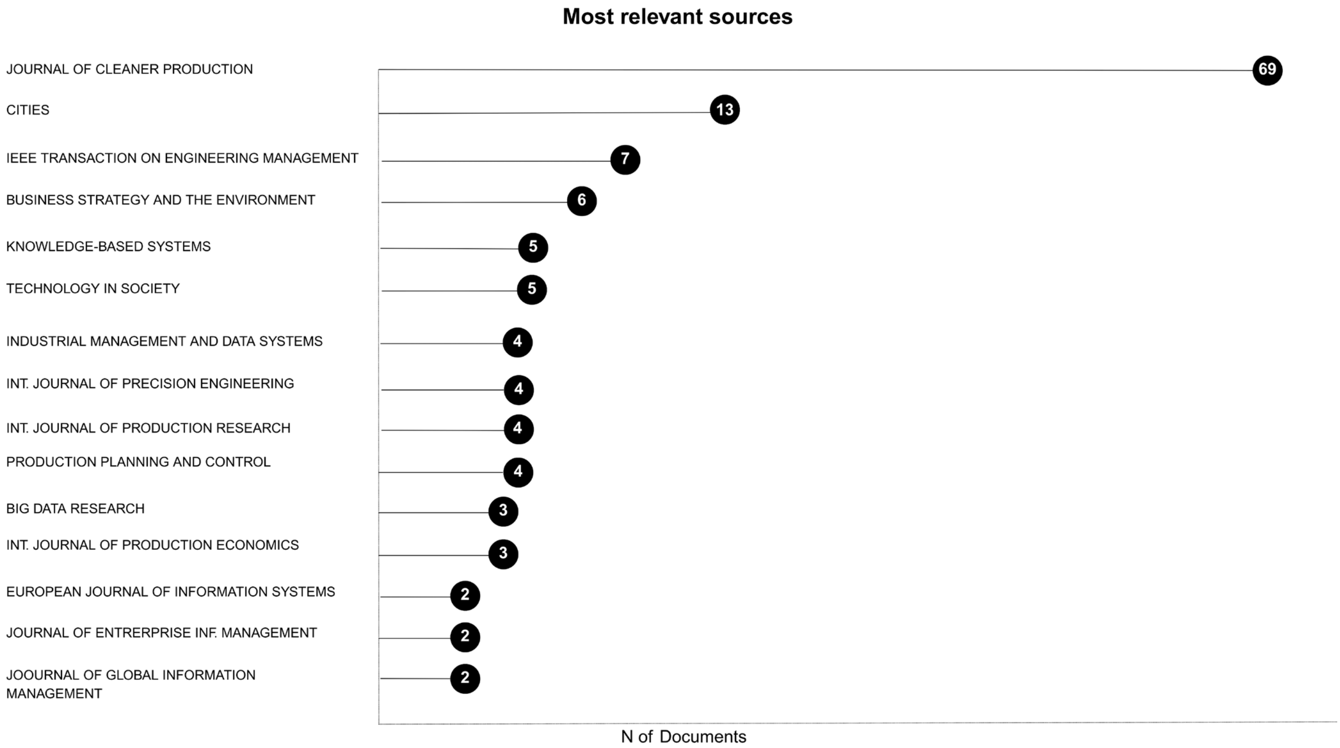

FIGURE 4 | Top 15 productive journals (Tier A).

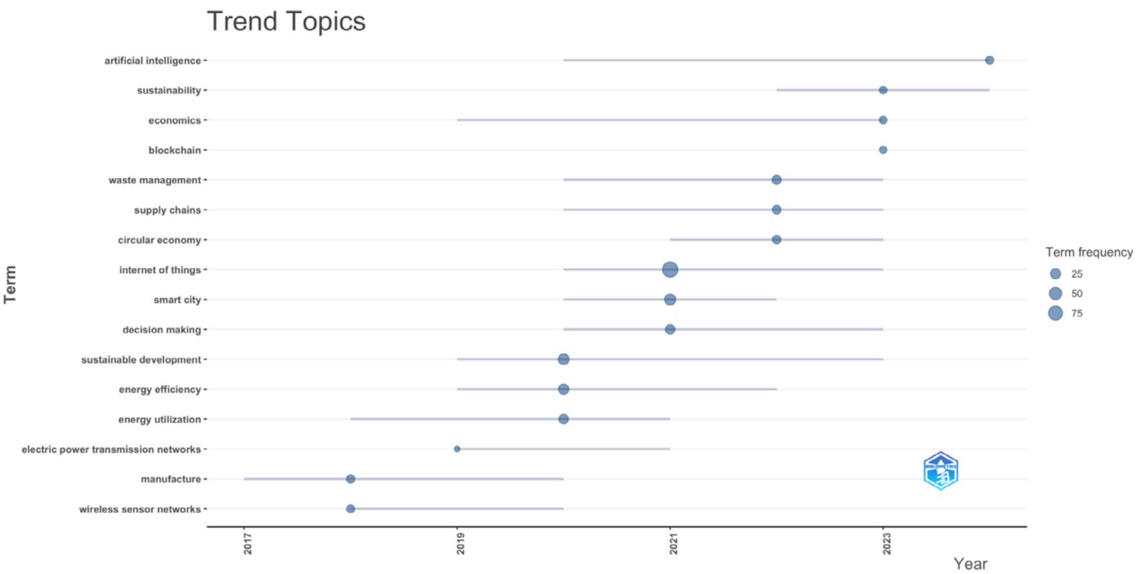

FIGURE 5 | Top 16 most frequent trend topics.

their importance and development within the dataset. By visualizing the relationship between centrality and density, the matrix facilitates a clearer understanding of both the maturity of the themes and their significance within the field (Rosenfield 1982).

The matrix is divided by two dimensions: *centrality*, indicating the importance of a theme within the dataset, and *density*, representing the development or evolution of the theme. In the upper-right quadrant, labeled "Motor Themes," we find topics like energy efficiency, energy utilization, and Big Data. Their high centrality and density indicate that these topics are well-developed and have broad applicability across multiple domains, significantly shaping both practical implementations and theoretical discussions. The influence of these themes is apparent in their widespread adoption in projects focusing on optimizing energy use, improving data processing capabilities, and contributing directly to sustainability goals. Because of their mature exploration, these themes act as pillars for current and future developments in the field, continually propelling innovation. In the upper-left quadrant, "Niche Themes," we see topics like electric power transmission networks, automation, and intelligent buildings. Although not as central, these themes are well-developed, suggesting they are specialized areas that have been thoroughly explored but

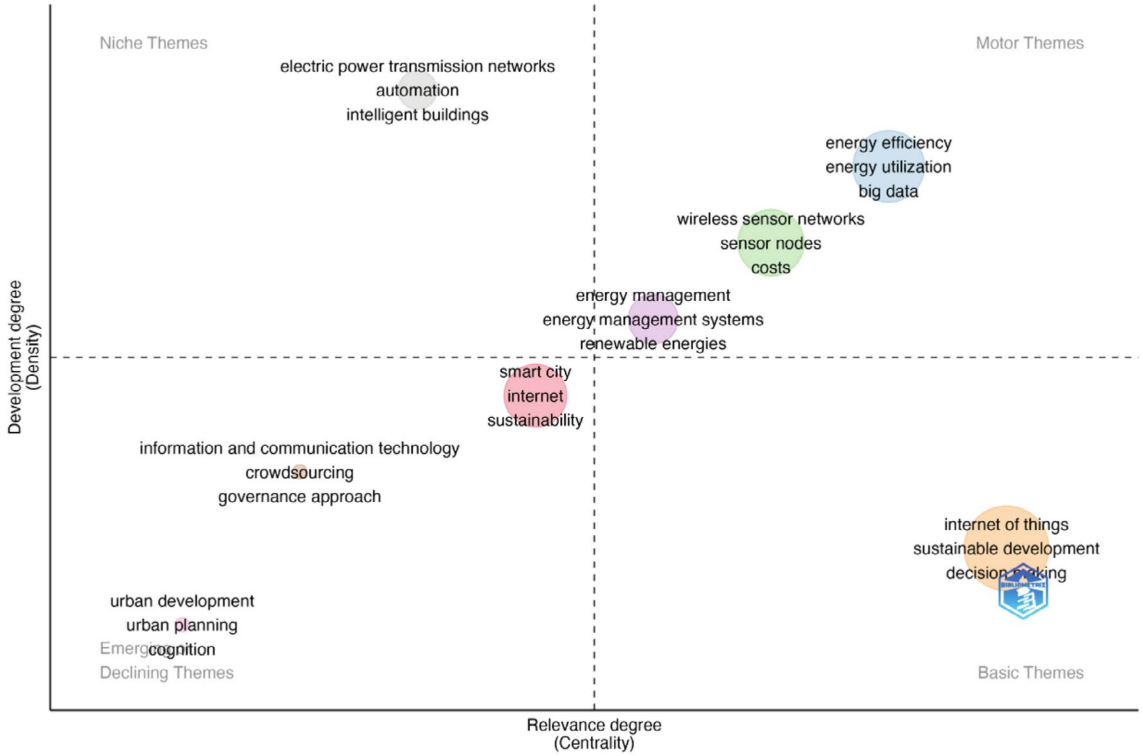

FIGURE 6 | Thematic map.

may not have as broad an impact across the field. Indeed, their high density indicates a rich depth of research, yet their lower centrality suggests that they are more specialized, focusing on particular technological advancements rather than broadly influencing the entire domain. Specifically, these themes contribute to niche areas of technology, such as enhancing automation efficiency in specific industries or optimizing power transmission at a localized level. Therefore, their importance is tied to specialized contexts where their utility is highly valuable, even if their overall field influence is limited.

In the lower-right quadrant, called "Basic Themes," we find IoT, sustainable development, and decision-making. These themes are foundational because they provide essential building blocks that underpin broader advancements within the field. The IoT, for instance, serves as a cornerstone technology that supports a wide array of applications, while sustainable development continues to shape strategic considerations in multiple disciplines. Despite their fundamental nature, these themes are still evolving and require further research to fully capitalize on their potential impact. Continued exploration into how IoT can facilitate seamless integration across different industries, or how sustainable practices can be further embedded in technological processes, will be the key for leveraging these areas for future growth. Finally, in the lower-left quadrant, "Emerging or Declining Themes," we see concepts like urban development, urban planning, and cognition. These themes occupy a critical space where their future trajectory could lead to greater prominence. Urban development and urban planning may be considered emerging as they align with the growing emphasis on sustainable urban environments and smart city initiatives. However, these themes still require significant advancements to solidify their place as central components of the discourse. On the other hand, cognition might be at risk of becoming less relevant if it is not further integrated into broader technological frameworks such as AI and IoT.

The thematic map reveals a growing body of research, which can be divided into several key areas. Among the most prominent authors in the field of Circular Economy and IoT is Murray et al. (2017), who defined the Circular Economy as "an economic model where planning, sourcing, production, and reprocessing are designed and managed to maximize ecosystem functioning and human well-being" (p. 369). This theme is particularly relevant in the context of IoT, which aims to enhance system efficiency through smarter resource management. Kristoffersen et al. (2020) further expanded on this theme, highlighting how business analytics capabilities are essential for implementing effective circular strategies. Their work points to the need for better understanding and advanced tools to bridge gaps in resource management through IoT. Specifically, they developed a theoretical and practical framework instrumental in defining a common language for interdisciplinary alignment between circular economy and information systems. Moreover, this framework helps identify discrepancies between existing and required capabilities, facilitating the adoption of best practices for smart circularity. Fatimah et al. (2020) investigated the topic by examining the feasibility of the circular economy in more complex contexts, such as Indonesia, where regulatory, infrastructural, and technological challenges represent significant barriers. They emphasized how Industry 4.0 technologies, including IoT and automation, can be integrated to build effective and sustainable waste management systems. Shrouf and Miragliotta (2015) also contributed to this discussion by focusing on the barriers to adopting smart waste management systems, specifically in China. The main challenges identified include a lack of knowledge and a scarcity of cooperation among stakeholders, which hampers the large-scale adoption of circular practices. Zhang et al. (2019) further emphasized the importance of collaboration between governments and companies to overcome regulatory barriers, noting the lack of legislative clarity as one of the most significant obstacles.

Another key topic explored in the literature is the relationship between IoT and Smart Cities. This theme has gained momentum in recent years, with contributions like Hashem et al. (2016), who highlighted the importance of Big Data in the implementation of smart cities. In particular, they argue that Big Data and IoT provide a platform to enhance urban life quality through more informed and integrated resource management. Allam and Dhunny (2019) extended this work by including Artificial Intelligence as an integral part of smart cities, emphasizing how urban governance, cultural dimensions, and urban metabolism are critical to implementing intelligent and sustainable cities. Wang and Banzhaf (2018) contributed to this stream of research by focusing on water resource management in smart cities. They discover that the use of sensors for real-time monitoring allows for more efficient water resource management and contributes to urban sustainability. Camero and Alba (2019) further explored the convergence between smart cities and green cities, suggesting that integrating enabling technologies such as IoT and Big Data could improve urban quality of life and help achieve sustainable development goals.

The third research area involves the integration of AI, Big Data, IoT, and other digital technologies in Industry 4.0. Nižetić et al. (2021) explored the challenges and opportunities arising from the integration of these technologies to enhance sustainability and operational efficiency. They emphasize how the convergence of AI, Big Data, and IoT is critical for addressing environmental and social challenges and promoting more sustainable practices. Li et al. (2020), on the other hand, highlighted the importance of a strategic approach in adopting digital technologies to enhance supply chain sustainability. Brown et al. (2021) investigated the integration of Big Data and machine learning in manufacturing industries, focusing on predictive management to improve operational efficiency and reduce costs.

To conclude, it is worth noting that Table 3 provides a visual representation of the most cited publications and the main issues they address. This table offers a structured overview, allowing for a clear understanding of the key themes and contributions in the literature on IoT and AI, IoT–Energy Efficiency and Circular Economy, and IoT and Smart Cities within the context of technological advancement and business strategy development.

4.4 | Co-Citation Network Analysis

To deepen the understanding of the field's intellectual structure, we performed a document-level co-citation network analysis. This method identifies documents that are frequently cited together within the literature, allowing us to uncover the underlying theoretical foundations and scholarly communities that shape the research domain (Boyack and Klavans 2010).

The resulting co-citation network revealed three major clusters, each representing a distinct intellectual domain within the field of IoT and sustainability research.

Cluster 1 groups together works by authors such as Liu and Wang (2021), Zhang et al. (2019), and Tao et al. (2014), who have extensively contributed to the application of IoT technologies for sustainable operations and data-driven decision-making. The core literature in this cluster addresses the use of IoT in smart agriculture, environmental monitoring, and optimization of operational efficiency through real-time scheduling systems. These contributions are characterized by their emphasis on the integration of IoT with advanced analytics and machine learning, aimed at improving both environmental performance and resource management.

Cluster 2 is anchored in the foundational theories of IoT and Circular Economy, with highly co-cited references by Atzori et al. (2010), Gubbi et al. (2013), and Ghisellini et al. (2016). This cluster reflects the conceptual grounding of the field, addressing topics such as IoT architecture, interoperability, and the systemic design of circular value chains. These works provide the theoretical scaffolding upon which much of the applied research builds, positioning IoT as a key enabler of sustainable and closed-loop systems.

Cluster 3 focuses on the technological infrastructure supporting IoT applications, particularly in urban and smart city contexts. Authors like Li et al. (2015) and Zanella et al. (2014) are central to this cluster, contributing to the development of communication protocols, M2M systems, and sensor networks. Their research highlights the technical challenges and design considerations involved in scaling up IoT for smart governance, environmental sensing, and urban data integration.

Figure 7 illustrates the document-level co-citation network and highlights the central authors within the intellectual landscape of IoT and ES research.

4.5 | Theoretical Integration Through the MLP

Building on the thematic and co-citation analyses presented above, we employed the MLP (Geels 2002) to structure the interplay between the conceptual and intellectual dimensions of the literature and reveal how the interplay between niche innovations, regime structures, and landscape pressures shapes the developmental trajectory of IoT technologies in relation to ES. Applying this framework has allowed us to move beyond a thematic mapping of applications and instead examine how the diffusion of IoT is embedded within broader socio-technical transitions. At the landscape level, many of the studies emphasize the influence of macro-level forces such as the twin transition as well as policy mandates, climate imperatives, and global sustainability agendas (European Commission 2020; Mu and Antwi-Afari 2024). These exogenous pressures act as destabilizing factors for incumbent systems and provide enabling conditions for technological experimentation and institutional change. The literature increasingly reflects how such pressures create momentum for IoT-enabled

TABLE 3 | Synthesis of the most significant publications and relative findings according to each trajectory.

Trajectory	Article	Title	Citations	Normalized citations
IoT, Energy Efficiency and Circular Economy	Srbinovska et al. (2015)	Environmental parameters monitoring in precision agriculture using wireless sensor networks	391	1.15
	Kristoffersen et al. (2020)	The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies	364	3.14
	Fatimah et al. (2020)	Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia	336	2.90
	Zhang et al. (2019)	Barriers to smart waste management for a circular economy in China	260	1.52
	Awan et al. (2021)	Industry 4.0 and the circular economy: A literature review and recommendations for future research	267	4.47
	Park et al. (2016)	Machine learning-based imaging system for surface defect inspection	255	0.96
	Avancini et al. (2019)	Energy meters evolution in smart grids: A review	232	1.36
IoT and Smart Cities	Hashem et al. (2016)	The role of Big Data in smart city	792	2.99
	Allam and Dhunny (2019)	On Big Data, artificial intelligence and smart cities	648	3.80
	Li et al. (2020)	The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model	450	3.88
	Camero and Alba (2019)	Smart City and information technology: A review	279	1.63
	Scuotto et al. (2016)	Internet of Things: Applications and challenges in smart cities: a case study of IBM smart city projects	238	0.89
Interconnections of IoT, AI and Big Data	Nižetić et al. (2020)	Internet of Things (IoT): Opportunities, issues and challenges toward a smart and sustainable future	474	4.09
	Li et al. (2020)	The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model	450	3.88
	Kamble et al. (2019)	Modeling the internet of things adoption barriers in food retail supply chains	230	1.34
	Srai et al. (2016)	Distributed manufacturing: scope, challenges and opportunities	220	0.83
	Zhang et al. (2017)	A framework for Big Data driven product lifecycle management	192	1.78
	Shrouf and Miragliotta (2015)	Energy management based on Internet of Things: practices and framework for adoption in production management	285	0.84
	Alcayaga et al. (2019)	Toward a framework of smart-circular systems: An integrative literature review	179	1.05

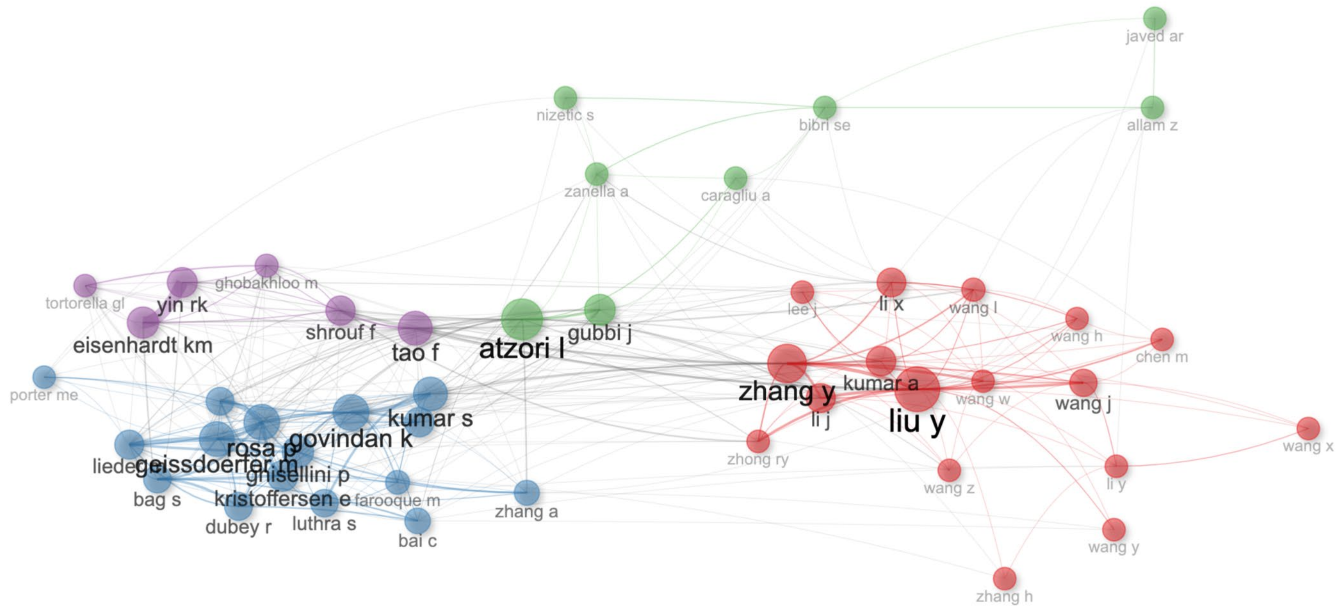

FIGURE 7 | Co-citation network analysis.

TABLE 4 | Thematic mapping of key literature contributions across MLP levels.

MLP level	Focus	Main contributions
Landscape	Macro-policies and digital transition	European Commission (2020), UNEP (2019)
	Societal narratives and climate agendas	Schot and Steinmueller (2018), Cambra-Fierro et al. (2024)
	Operationalization of sustainability goals	Mondejar et al. (2021), Agrawal et al. (2022)
Regime	Governance and standardization barrier	Kamble et al. (2019), Pang et al. (2015)
	Interoperability across sectors	Ingemarsdotter et al. (2020), Rejeb et al. (2022)
	Policy-technology coordination	Zhang et al. (2019), Fatimah et al. (2020)
Niche	Precision agriculture pilots	Khanna and Kaur (2019), Bouguettaya et al. (2023)
	Smart waste and circular pilots	Mboli et al. (2022), Fatimah et al. (2020)
	Blockchain-IoT experimental models	Shi et al. (2020), Singh et al. (2020)

sustainability practices, aligning technological innovation with broader policy shifts and environmental goals.

Moving to the regime level, our review indicates a growing integration of IoT within established sectors such as agriculture, energy, urban infrastructure, and waste management. These studies often document the partial embedding of IoT solutions into dominant practices—such as precision farming, real-time grid management, or urban monitoring systems—illustrating a process of incremental adaptation rather than radical disruption. However, several contributions also highlight enduring barriers, including technological fragmentation, lack of interoperability, and institutional lock-ins that limit the full realization of IoT's transformative potential (Kamble et al. 2019; Pang et al. 2015). These regime-level constraints are particularly pronounced in public infrastructure systems, where organizational inertia and regulatory complexity hinder cross-sectoral integration.

At the niche level, we identified a rich set of experimental initiatives and early-stage applications, often situated in research-led pilots or innovation-driven municipalities. These include examples such as UAV-based precision agriculture, IoT-enhanced waste monitoring, and blockchain-integrated sustainability platforms (Zhang et al. 2018; Anagnostopoulos et al. 2017; López-Vargas et al. 2020). Many of these innovations are supported by protective institutional mechanisms—such as living labs, sandboxes, or targeted funding—that allow them to evolve relatively free from market or regulatory pressures. Some studies also provide evidence of niche-regime interactions, where successful pilots inform policy design or are scaled up through partnerships with regime actors, suggesting early signs of transition dynamics.

By organizing the literature across MLP's three analytical levels, we gain a finer understanding of how IoT contributes to or is constrained within sustainability transitions. The findings suggest that while landscape pressures are creating opportunities, regime-level inertia often slows systemic transformation, and niche innovations—though promising—remain fragmented and context-specific. This multi-scalar analysis highlights the importance of coordination across levels: niche innovations require alignment with landscape trends and regime support to scale and stabilize, while regimes need to open pathways for innovation through policy, standards, and institutional reform. Table 4 offers a structured synthesis of the main thematic areas emerging from the literature (see Table 3), reclassified according to the MLP framework. It illustrates how key contributions are distributed across landscape, regime, and niche levels, thereby supporting a more granular interpretation of IoT's role in sustainability transitions.

5 | Discussion

From the bibliometric analysis of the literature and the qualitative content analysis of the most influential papers on the subject, this review paper has identified four mainstream research topics concerning the relationship between IoT and ES: (i) application of IoT for ES in agriculture and smart waste management; (ii) the impact of IoT on Circular Economy; (iii) the role of IoT in Smart Cities; (iv) the convergence between IoT, AI, and Big Data.

5.1 | Application of IoT for ES in Agriculture and Smart Waste Management

The application of IoT in precision agriculture has led to a significant breakthrough in terms of ES. Indeed, IoT technologies such as Wireless Sensor Networks (WSN) and RFID systems enable the collection of real-time data on environmental conditions, allowing farmers to make more informed and precise decisions regarding crop growth (Srbinovska et al. 2015). Furthermore, as highlighted by Khanna and Kaur (2019), these tools promote more efficient resource use by optimizing irrigation systems and monitoring soil and crop health with unprecedented precision. This not only reduces water and energy consumption but also minimizes the environmental impact of agriculture, a traditionally resource-intensive sector (Tukker et al. 2016). Bouguettaya et al. (2023) and Liu and Wang (2021) further contribute to this topic by emphasizing how deep learning models based on high-resolution images and environmental sensors improve the timeliness and accuracy of agronomic interventions, further reducing the ecological impact. Another key contribution of IoT in agriculture relies on the management of the agricultural supply chain, where RFID technologies simplify the tracking of products throughout the transportation process. Wang (2012) and Khanna and Kaur (2019) demonstrated how these systems enhance logistical efficiency and reduce waste, ensuring more efficient resource use during transportation and distribution. Moreover, the ability to monitor the movement of agricultural products in real time ensures better quality and freshness of food, reducing the energy footprint of the logistical chain and contributing to overall sustainability. Finally, it is worth noting that the integration of IoT with Artificial Intelligence (AI) and Big Data has further expanded the potential of precision agriculture. According to Saranya et al. (2023), the use of Unmanned Aerial Vehicles (UAV) and smart sensors, combined with deep learning models, allows for early detection of diseases and pests in crops, thus reducing excessive use of pesticides and fertilizers. This innovation promotes more sustainable pest control strategies and reduces soil and water contamination, fostering a more environmentally friendly approach.

Another significant contribution offered by IoT to ES, particularly emphasized in research, relates to the field of smart waste management. The adoption of IoT in intelligent waste management systems has led to considerable improvements, enabling more efficient and effective management of urban waste collection (Fatimah et al. 2020). Specifically, as highlighted by Gopi et al. (2021), the use of ultrasonic sensors to monitor waste levels in bins, combined with cloud platforms such as Blynk, not only allows for timely detection of bin capacity but also facilitates notifications to relevant authorities, optimizing waste collection routes. This technology significantly reduces the risk of waste overflow, helping to maintain urban cleanliness and mitigate negative public health impacts. Furthermore, through GSM or GPRS connections and IoT sensors, waste bins can be remotely monitored, with alerts sent to responsible parties, ensuring timely intervention and reducing the need for frequent manual inspections (Srikanth et al. 2019). In doing so, smart waste collection not only optimizes resource use but also helps to reduce pollution, enhancing the overall livability of cities (Mdukaza et al. 2018). Another critical aspect is the integration of IoT with cloud computing and Big Data for the analysis of data collected by sensors (Shyam et al. 2017). Indeed, the interconnection between these technologies and cloud platforms allows for both real-time data storage and visualization while also facilitating the identification of predictive models, enabling forecasts of where and when waste will be produced in excess. This approach supports more informed decision-making and further reduces operational costs through targeted and preventive interventions (Deepak et al. 2021).

5.2 | The Impact of IoT on Circular Economy

Another topic extensively addressed by research is the relationship between the IoT and the Circular Economy (CE). The IoT plays a key role in promoting CE, as it enables real-time monitoring and management of product and resource life cycles. In this regard, IoT operates both upstream and downstream of the product life cycle. Awan et al. (2021) have highlighted how IoT enables predictive maintenance of assets, thereby extending their life cycle and reducing operational costs, with a direct impact on business sustainability, particularly in upstream processes. On the other hand, Rusch et al. (2023) demonstrated that the integration of IoT with Big Data in industrial processes can optimize recycling and material recovery processes, making production systems more circular and efficient. Supporting these claims, Reuter (2016) introduced the concept of the Metallurgical Internet of Things (m-IoT), emphasizing how the digitalization of global metallurgical processes allows for maximizing the recovery of technological and mineral resources, improving traceability and efficiency across the entire production system. Similarly, in remanufacturing processes, IoT has been shown to facilitate operations such as dismantling without damaging materials (Alcayaga et al. 2019). For these reasons, IoT is considered an enabler for the design of more efficient recycling systems, capable of improving recycling rates and optimizing waste reuse (Mboli et al. 2022). Regarding the adoption of IoT in the CE, one enabling factor of this technology is its capacity to foster collaboration between companies and facilitate servitization, where products are offered alongside preventive maintenance and life-cycle extension services. Additionally, IoT increases transparency and operational efficiency in circular supply chains, reducing operational costs and enhancing corporate competitiveness (Rejeb et al. 2022). However, as highlighted in previous thematic clusters, barriers such as the lack of interoperability among IoT devices and the need for advanced technical skills to manage the generated data represent significant limitations to adoption (Ingemarsdotter et al. 2020). In this context, Esmaeilian et al. (2020) emphasize that current weaknesses in decision-making processes and data management hinder the full exploitation of the potential of Big Data generated by IoT systems.

5.3 | The Role of IoT in Smart Cities

Analyzing the use of IoT in Smart Cities, it is evident that this is one of the most compelling and widely debated research topics. Numerous authors have explored the impact of IoT in Smart Cities from various perspectives, highlighting a range of applications and challenges. Among the most noteworthy studies concerning urban districts, Deakin and Reid (2018) focused specifically on digital infrastructure and cloud computing systems. The author examined the case of Hackbridge, a district in London that has implemented IoT technologies to improve energy efficiency and quality of life. Deakin emphasized how the integration of IoT and data management technologies facilitates sustainable urban planning but also stressed the importance of considering social equity in the distribution of technological benefits. Similarly, White et al. (2021) studied the use of IoT in managing water resources and transportation systems across various cities. Their research was based on the use of IoT sensors to monitor and optimize water distribution and waste management, thereby improving urban resilience. However, they also highlighted that IoT networks are vulnerable to cybersecurity issues, and the maintenance of technological infrastructure remains a critical challenge. Another interesting study examined the relationship between IoT and urban resource management in China, which presents a notably different context compared to Europe. The authors developed a Smart City framework based on Big Data analysis, demonstrating how the integration of information technologies such as cloud computing and IoT can enhance the efficiency of urban infrastructure, including transport systems and energy resources. This approach contributes to reducing CO_2 emissions and creating more resilient cities (Wu et al. 2018). Scuotto et al. (2016), on the other hand, studied several urban projects led by IBM, one of the leading companies in the Smart City landscape due to its strategic vision and implementation of innovative projects across multiple cities worldwide. Their analysis focused on the role of IoT in implementing Open Innovation models within Smart Cities, showing how IoT, combined with open innovation strategies, enables cities to leverage external resources to co-create value and technological solutions. This approach involves various stakeholders, including businesses, universities, and local governments, enhancing urban quality of life and business innovation. Regarding the contribution IoT can offer to the private sector, a significant study by Javed et al. (2022) explored the use of IoT in energy management within smart homes. The authors examined how IoT devices, such as Google Home and Alexa, can monitor and optimize energy usage in homes, reducing waste and costs. Their research was based on case studies of smart home implementations in developed cities, providing concrete insights into the potential and challenges related to the standardization and interoperability of IoT systems. Lastly, in a completely different context, Herath and Mittal (2022) examined the use of IoT in managing urban health emergencies during the COVID-19 pandemic. Their study focused on the application of telemedicine and IoT devices for remote monitoring of citizens' health conditions. The authors demonstrated how these technologies helped alleviate the burden on healthcare facilities and improved access to medical services during the pandemic. However, although all the studies reviewed have identified IoT as a strategic and essential technology for realizing the full potential of Smart Cities, it is necessary to underscore that challenges related to data security and technological infrastructure maintenance have emerged as common issues. From Wu et al. (2018), who highlighted risks associated with information protection, to White et al. (2021), who underscored the vulnerability of IoT networks to cybersecurity threats, each study has pointed to the necessity of addressing these aspects to ensure the success and sustainability of Smart Cities. Even Scuotto et al. (2016) recognized the difficulty of balancing innovation with intellectual property protection and secure data sharing between public and private partners in their study of IBM projects.

5.4 | An Eye to the Future: The Convergence Between IoT, AI, and Big Data

An additional area of study is dedicated to exploring the prospective developments of IoT possibilities. In fact, this technology is rapidly evolving, projecting itself toward a future where interconnection with other key technologies, such as AI, Big Data, Cloud Computing, and blockchain, will be central to its full realization. It is clear that this convergence not only enhances IoT's capabilities but also broadens its application field, transforming key sectors like smart cities, manufacturing, and construction. In this context, regarding smart cities, Shi et al. (2020) and Sharma et al. (2021) provide a clear perspective on the importance of integrating IoT with AI in urban service management. Specifically, Shi et al. (2020) focus on how AI can optimize IoT networks, reducing overload and improving efficiency in the management of critical infrastructures, such as traffic and energy. Sharma et al. (2021), on the other hand, add another layer of complexity by integrating blockchain to ensure security and data transparency in IoT transactions, making smart cities not only more efficient but also safer and more resilient. Similarly, in the construction sector, Rane (2023) demonstrates how AI, combined with IoT and blockchain, can transform the planning and execution of construction projects. Specifically, AI through IoT is used to optimize resources and reduce operational costs, while blockchain ensures transparency and security in data flows. On the technical side, Firouzi et al. (2022) delve into the analysis and distributed infrastructure for managing the data generated by IoT, arguing that the integration of AI with cloud, edge, and fog computing architectures allows for more efficient management of data flows, reducing latency and improving predictive analysis. This is particularly relevant for applications that require real-time response, such as remote monitoring or predictive maintenance. Firouzi et al. (2022) also provide a technical vision of how distributed infrastructures can be designed to support scalable and high-performing IoT applications. Also, in the study by Singh et al. (2020), blockchain technology plays a central role in enhancing the security and trust of distributed IoT networks. They explore how blockchain can be used to manage and secure the large volumes of data generated by IoT devices, especially in environments where data privacy and integrity are fundamental, such as smart cities and sensor networks. Singh et al. focus on smart contracts as a key application of blockchain for automating transactions and ensuring data transparency within IoT ecosystems. These smart contracts allow IoT devices to autonomously interact with each other and execute predefined actions when certain conditions are met, without requiring intermediaries. This not only improves the efficiency of IoT networks but also reduces the risk of unauthorized access or data tampering. Moreover, turning to the manufacturing sector, this represents another example of the effective convergence between IoT, AI, and Big Data. In fact, through "digital twins," which provide a virtual representation of physical processes and enable predictive analysis and optimized management of production, operational efficiency can be improved, and downtime can be reduced through predictive maintenance, demonstrating how AI can be applied in highly industrialized contexts through IoT simulations (Kaur et al. 2020).

5.5 | Main Addressed Research Questions

From the content analysis of the works examined in the literature review, it is evident that certain research questions have been particularly addressed by the literature, indicating that they are perceived as relevant by scholars in the field. Among these, one of the key questions concerns the integration of digital technologies with circular economy strategies in manufacturing contexts (Schöggl et al. 2023; Awan et al. 2021). The current literature acknowledges the potential of IoT in improving energy efficiency and optimizing resources, but it remains unexplored how these technologies can be systematically integrated into operational and tactical decision-making processes (Kamble et al. 2019). Similarly, there is an urgent need to develop advanced analytical capabilities that support intelligent circular strategies, enabling more effective resource management and greater operational sustainability (Kristoffersen et al. 2020). Specifically, in the realm of smart agriculture, research focuses on optimizing and implementing low-cost, low-maintenance wireless sensor networks that can sustain long-term operations, particularly in agricultural contexts where energy efficiency and cost reduction are essential (Srbinovska et al. 2015). Parallel research questions have also developed around waste management and the development of smart cities. Specifically, there is a need to better understand the specific barriers that hinder the transition to a circular economy in various regions, especially in China and Indonesia, where cultural and regulatory factors can significantly influence the adoption of smart technologies (Fatimah et al. 2020). To address this, research has attempted to develop interdisciplinary collaboration models and frameworks that integrate information and communication technologies (ICT) with governance and sustainable economic development strategies (Zhang et al. 2019). Finally, regarding security, governance, and standardization, the literature has investigated the need for scalable architectures and advanced algorithms that enhance the efficiency of Big Data solutions in urban contexts (Bibri and Krogstie 2017).

5.6 | Gaps and Further Research Avenues

The insights derived from our analysis have allowed us to identify targeted research directions across the niche, regime, and landscape levels, revealing where scholarly attention and institutional effort are most urgently required. By linking these directions to the systemic dynamics outlined in the MLP, we propose a theoretically coherent roadmap for future research and policy development. The following research questions and strategic implications, originally discussed separately, are now structured across the MLP levels to better support theoretical consistency and actionable development.

5.6.1 | Niche Level: Experimental Applications and Validation

At the niche level, our review revealed a wide range of experimental IoT applications, often localized, temporary, or emerging within innovation-led policy contexts. These include initiatives in precision agriculture, smart energy, waste monitoring, and urban resilience. While promising, these innovations tend to remain technologically isolated or institutionally unsupported, rarely maturing into fully operational, scalable systems.

The discrepancy between theory and practice is clearly evident in the validation of theoretical models concerning IoT and sustainability. Many existing studies focus on theoretical frameworks without providing robust empirical validation through case studies or field research. This lack of practical validation limits the ability to successfully apply theoretical strategies in real-world contexts, creating a gap that needs to be bridged through greater emphasis on experimentation and empirical documentation. As a result, the following research question arises.

Q1. *What are the key challenges in translating theoretical IoT-based sustainability models into practical applications, and how can these challenges be systematically addressed through field research and case-based validation?*

5.6.2 | Regime Level: Integration, Governance, and Standardization

At the regime level, the literature elucidates how IoT is being integrated into established infrastructures across agriculture, energy, mobility, and urban systems. However, this integration is often irregular and fragmented, constrained by legacy infrastructures, regulatory inertia, and the absence of harmonized standards.

In particular, the first gap pertains to the absence of a systematic methodological framework that effectively links IoT with ES strategies. Although IoT is widely recognized as a central enabler of ES, the current literature highlights a lack of comprehensive guidelines on how this technology can be strategically applied to fully leverage the potential of circular strategies, particularly in industrial contexts where the integration of digital solutions remains underexplored. This lack of integration also extends to the context of smart cities, where technological fragmentation presents a significant challenge. Despite the considerable potential of IoT, Big Data, and other digital technologies to enhance urban environments, there is a pronounced disconnection in how these technologies are implemented. Such fragmentation hinders the achievement of ES goals at the urban level, complicating the ability to address the complex technical and commercial challenges inherent in smart cities. The following research questions emerge from this gap:

Q1. *How can the data flows generated by IoT devices be optimized to support the transition toward a circular production model in manufacturing industries, while simultaneously reducing environmental impact?*

Q2. *How does technological fragmentation within smart cities affect the collection and processing of environmental data from IoT devices, and what interoperability models can be developed to overcome these barriers?*

Q3. *What are the key variables that determine the successful integration of IoT and Big Data into urban sustainability policies, and how can they be leveraged to design strategies that proactively address the specific environmental challenges of developing cities?*

In addition to systemic integration, other regime-level barriers hinder IoT-enabled ES adoption, such as limited analytical capabilities and operational inefficiencies in sensor-based networks. Specifically, the literature reveals a shortage of research focused on how to develop and utilize business analytics tools to optimize resource management and improve operational efficiency within the context of the circular economy. This aspect is closely linked to the need to enhance organizations' ability to harness data-driven insights gathered through IoT to support more informed and sustainability-oriented decision-making. Consequently, a related issue that arises is the optimization of energy consumption, particularly concerning sensor networks used for environmental monitoring. Many current systems do not adequately address energy efficiency, compromising their long-term sustainability, especially in contexts such as agriculture, where battery replacement is complex and costly. Therefore, some future research questions could examine:

Q1. *What are the most effective methods for integrating data-driven insights from IoT-enabled systems to support sustainability-oriented decision-making in organizations, and how can these methods be systematically implemented across industries?*

Q2. *How can the energy consumption of sensor networks used in environmental monitoring be optimized to ensure long-term sustainability, particularly in sectors such as agriculture, where operational constraints make battery replacement a significant challenge?*

Another shared gap highlighted by the research is the lack of standardized procedures and integration among different digital technologies. This represents a significant obstacle, as the absence of shared standards and interoperability frameworks creates substantial barriers to the large-scale adoption of smart technologies. Without these standards, integrating diverse technological platforms becomes problematic, limiting the effectiveness and scalability of solutions, particularly for smart cities. This gap leads to the following research questions:

Q1. *What standardization frameworks and interoperability protocols need to be developed to facilitate the seamless integration of diverse digital technologies in smart cities, and how can these frameworks enhance the scalability and effectiveness of IoT solutions for environmental management?*

Q2. *What are the key technical and organizational challenges in creating interoperable IoT systems for environmental management, and what strategies can be employed to overcome these barriers and ensure consistent data flow and system integration across platforms?*

Building on these interoperability challenges, our findings also point to the need for research focused on institutional alignment and governance innovation. In particular, questions emerge around how digital infrastructures and sustainability policies can be better coordinated across sectors, how organizations build the absorptive capacity to engage with complex IoT ecosystems, and what role state actors, municipalities, or international bodies might play in fostering more integrative and interoperable frameworks. Analyzing the governance models underpinning successful cross-sectoral IoT integration, especially those involving public-private partnerships or transdisciplinary governance platforms, could help reveal the conditions under which regime change becomes possible. Altogether, these challenges at the regime level underscore the importance of coordinated governance, technological standardization, and institutional learning in enabling IoT-driven sustainability transitions.

5.6.3 | Landscape Level: Macro-Trends and Societal Discourses

At the landscape level, we observed increasing attention to the macro-trends shaping IoT's sustainability potential: the twin transition paradigm, climate urgency, global decarbonization agendas, and the expansion of digital infrastructure. These landscape forces are often framed as exogenous pressures that generate opportunities for innovation, but their influence on IoT development remains under-theorized in much of the empirical literature. A deeper investigation is needed into how global sustainability narratives, policy frameworks (such as the European Green Deal), and shifting public expectations shape the directionality of IoT development.

This includes studying how these pressures are translated into national strategies, local implementation mechanisms, and organizational visions. Additionally, research could benefit from examining how societal discourses, especially those surrounding trust, surveillance, and environmental justice, influence the legitimacy and uptake of IoT solutions aimed at sustainability goals. Collectively, these macro-level forces provide the broader context that indirectly shapes the trajectories of regime-level

TABLE 5 | Overview of research gaps, questions, and multi-level dynamics in IoT-enabled environmental sustainability.

Research area	Thematic clusters	Core issues	Identified research questions	MLP level(s) involved	Key actors/ Stakeholders
Systemic Integration of IoT and ES	Smart Cities; Circular Economy	Lack of methodological frameworks linking IoT with ES strategies; technological fragmentation in urban systems	Q1: How can IoT data flows be optimized to support circular production? Q2: How does fragmentation impact data integration in smart cities?	Regime/Landscape	Urban planners, policymakers, smart city integrators
Analytical Capabilities and Business Models	IoT, Big Data and Artificial Intelligence for Decision Making	Limited development of data-driven business analytics; energy inefficiency in environmental sensor networks	Q1: What methods best integrate IoT data insights for sustainable decisions? Q2: How can sensor energy consumption be minimized for long-term use?	Niche/Regime	Business strategists, data scientists, environmental engineers
Practical Applications and Validation	Waste Management; Precision Agriculture	Scarcity of empirical validations and real-world case applications of IoT-ES theoretical models	Q1: What are the challenges in translating theoretical models into field-tested applications, and how can they be systematically addressed?	Niche	Academics, municipal project managers, NGOs
Standardization and Interoperability	Smart cities and smart infrastructures	Absence of shared standards; difficulty in achieving interoperability across diverse digital infrastructures	Q1: What frameworks are needed to ensure digital interoperability in smart cities? Q2: What organizational and technical challenges hinder IoT system integration?	Regime	Standardization bodies, IT architects, regulatory agencies

change and niche experimentation in IoT-enabled sustainability transitions.

Table 5 synthesizes the key research areas emerging from the literature, mapping them onto relevant thematic clusters, core unresolved issues, and corresponding research questions. Each area is also situated within the appropriate MLP level(s) and associated with the key actors and stakeholders most directly involved.

6 | Strategic and Practical Implications

Beyond the academic implications, our findings yield several strategic insights for policymakers, practitioners, and institutional designers. Governments and regulators should foster digital ecosystems that are not only innovative but also interoperable, supporting modular architectures, open standards, and agile governance mechanisms capable of adapting to technological complexity. Regulatory sandboxes and policy experimentation zones may play a critical role in facilitating responsible deployment and scaling of IoT solutions.

Industry actors and practitioners, meanwhile, should invest in cross-technology convergence, particularly the integration of IoT with AI and blockchain, as a way to enhance systemic efficiency, real-time decision-making, and traceability across value chains. At the same time, more nuanced, sector-specific guidelines are needed to assist businesses in aligning IoT implementation with circular economy principles and environmental performance metrics.

Ultimately, researchers have a unique opportunity to shape this emerging field through the development of interdisciplinary methodologies that combine bibliometric techniques, empirical case studies, and socio-technical transition theories. Such approaches can illuminate the complex interplay between innovation dynamics, institutional evolution, and societal change—revealing not only where IoT is having an impact, but also how and under what conditions that impact becomes transformative.

7 | Conclusions and Limitations

This review stands among the earliest mixed-method investigations addressing the dynamic interaction between IoT and ES. By synthesizing bibliometric analysis, content mapping, and interpretive synthesis via the MLP, we construct a framework for understanding not only how IoT technologies respond to ES imperatives but also how they actively reconfigure innovation ecosystems. The inquiry surfaces four principal research domains: (i) IoT deployments in precision agriculture and intelligent waste systems; (ii) its central integration within Circular Economy paradigms; (iii) strategic inflections in Smart City infrastructures; and (iv) the nascent fusion of IoT with Artificial Intelligence, blockchain architectures, and Big Data analytics.

Theoretically, our contribution lies in embedding these findings within the layered logic of the MLP framework—exposing the pathways through which IoT-enabled transitions unfold across niche experimentation, regime stabilization, and landscape-level pressures. Practically, the implications are multiple: from algorithmic waste collection and sensor-based irrigation systems to predictive maintenance in urban grids. These examples, while varied, converge on a singular objective—designing resilient, scalable, and energy-efficient systems. For policymakers, our synthesis underscores the pressing necessity of forward-looking regulatory infrastructures that enable open standards, ensure interoperability, and embed digitalization within broader climate and decarbonization agendas.

Yet, for all its insights, this review faces a collection of unresolved tensions. Dominant among them: the under-theorized coupling of IoT and ES methodologies, the lack of empirical validations for conceptual models, and persistent interoperability bottlenecks. Addressing these gaps demands a recalibrated research agenda—one that champions interdisciplinary convergence, advances data-informed decision-making architectures, and pursues longitudinal case studies capable of tracing the lived impacts of IoT deployments across time and space.

Naturally, limitations attend our endeavor. The study's evidentiary base is delimited to English-language publications indexed in Scopus, with a primary concentration on Q1 Business and Management outlets. This scope, while rigorous, inevitably marginalizes perspectives from adjacent fields—engineering, ecological science, and non-English academic discourse among them. Additionally, although manual content analysis enabled interpretive richness, it may have introduced subjective inflections. To mitigate such limitations, future work should embrace multi-database sampling and hybrid methodologies that blend human coding with machine-driven content analytics—thereby enhancing robustness and reproducibility.

In an era marked by converging digital and ecological inflection points, this review offers a critical lens through which to envision the role of IoT in reshaping ES trajectories. By transcending disciplinary enclaves and offering both theoretical support and actionable insight, this work draws a roadmap for scholars, practitioners, and policymakers intent on forging a digitally mediated, environmentally regenerative future.

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