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Decoding the coffee supply chain: A systematic review of stakeholders, sustainability opportunities, and challenges

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ABSTRACT

The global coffee supply chain is undergoing significant sustainability transformations, driven by increasing environmental, social, and technological pressures. This study conducts a systematic literature review (SLR), guided by PRISMA criteria and complemented by a VOSviewer-based bibliometric analysis, to explore how sustainability is conceptualized and operationalized across the coffee value chain. Drawing from 137 peer-reviewed publications (2000–2024), the review addresses four interrelated research questions: (i) the roles and interactions of key stakeholders, (ii) cross-sectoral opportunities for coffee residue reuse, (iii) the influence of consumer preferences on market dynamics, and (iv) the adoption of digital technologies such as IoT, blockchain, and AI for transparency and traceability. Findings reveal that while sustainability discourse is expanding, the literature remains fragmented across environmental, socio-economic, and technological domains. The review identifies emerging clusters around agroecological practices, circular economy models, and digital traceability, emphasizing the need for integrated, multi-stakeholder strategies with priority research areas identified in agriculture, transportation, cosmetics, energy, and packaging. Limitations such as database coverage, potential selection biases, data variability and geographic representation are acknowledged. Future studies are encouraged to innovate and expand sustainable coffee practices to catalyze meaningful change. It also recognizes challenges like cost and scalability in implementing sustainable solutions, underscoring the need for continued research and multi-stakeholder collaboration to address these barriers effectively. The study concludes with actionable insights for researchers, practitioners, and policymakers to advance a cohesive and data-driven approach to sustainability in the global coffee sector.

Acronyms

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SLR	Systematic Literature Review
SCGs	Spent Coffee Grounds
IoT	Internet of Things
AI	Artificial Intelligence
GIS	Geographic Information Systems
RFID	Radio-Frequency Identification
SDGs	Sustainable Development Goals
EL	Eligibility Criteria
EX	Exclusion Criteria
FWCI	Field-Weighted Citation Impact
CSR	Corporate Social Responsibility

1. Introduction

The global economy is at a crossroads: on the one hand, the urgent need to reduce waste and environmental impact; on the other, the potential of digital technologies to transform entire supply chains. The coffee supply chain, one of the most complex and globalized, offers a unique window into these dynamics [1]. From cultivation to consumption, coffee passes through a complex network that involves millions of farmers, exporters, producers and consumers [2]. Coffee cultivation takes place in over fifty developing countries across Latin America, Africa, and Asia, serving as a vital source of income for approximately 20–25 million families globally [3]. With an estimated consumption

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surpassing 2.25 billion cups daily worldwide, coffee plays a central role in daily routines across the globe. In the United States, 76 % of adults are reported to be regular coffee consumers [4], while European nations boast some of the highest per capita consumption rates [5]. The initial stages of coffee production, involving farming, collection, and processing, are predominantly labor-intensive, making them well-suited for countries abundant in labor resources [6]. Conversely, the roasting and branding phases, which are more capital-intensive, are typically situated in industrialized countries in the northern hemisphere. The top five consumers of coffee include the United States of America, Brazil, Germany, Japan, and France [7].

Despite its global footprint, the coffee sector faces rising sustainability pressures, from environmental degradation and economic inequality to digital disruption and resource waste. These risks have intensified due to growing consumer scrutiny, climate instability, and complex stakeholder interdependencies. Yet, our understanding of how sustainability is evolving across the entire coffee value chain remains fragmented.

The structure of the coffee value chain remains relatively consistent regardless of the country involved in production or consumption. It comprises four primary phases: Cultivation, Processing, Roasting, and Consumption [8]. Each phase presents environmental, social, economic, and governance challenges that significantly impact the long-term sustainability of coffee production. At every step, factors such as weather patterns, labor dynamics, market demands, and technological advancements shape the intricate interplay of stakeholders, as emphasized by Peluso [9]. Challenges and opportunities abound, from farmers striving for high-quality crops to distributors navigating market shifts and transportation logistics. Simultaneously, consumer choices and environmental advocacy contribute to the dynamic landscape of the coffee supply chain [10].

What remains missing in the literature is a system-wide understanding of how sustainability transformations are taking shape in the coffee supply chain, particularly those involving digital technologies, circular reuse of residues, and evolving stakeholder roles [11]. This study directly addresses that gap by asking: What are the key sustainability shifts in the coffee supply chain over the past two decades, and how are they represented in the academic literature across sectors and disciplines?

While the sustainability of the coffee supply chain has been widely discussed, there remains a lack of consolidated knowledge that integrates technological innovation, stakeholder interdependence, and systemic challenges. The landscape of sustainability-related coffee supply chain reviews has expanded significantly in recent years, yet several critical gaps remain unaddressed. For instance, and Gebreeyessus [12] present valuable overviews of environmental practices and bioresource reuse but focus narrowly on either life cycle assessment (LCA) or bioeconomic reuse of spent coffee grounds, lacking any integrated discussion of stakeholder dynamics, digital innovation, and market behavior. Similarly, recent reviews such as Hejna et al. [13] and Rijo et al. [14] examine SCG valorization and technological reuse potential, yet they do not contextualize these within a system-level coffee supply chain perspective, nor do they evaluate stakeholder interdependencies or trace bibliometric shifts in the field.

Furthermore, most existing reviews omit bibliometric methodologies altogether. None to date have deployed VOS viewer-based co-occurrence analysis to uncover how themes like circular economy, digital traceability, or fair-trade certifications have evolved across time, geography, and disciplines. This omission leads to a conceptual blind spot, while practices and impacts are documented, underlying research trajectories, knowledge clusters, and thematic shifts remain underexplored, limiting foresight for both researchers and practitioners. To fill this gap, this study conducts a PRISMA-guided systematic literature review, enriched with bibliometric analysis, to evaluate how sustainability in the coffee supply chain is being conceptualized and operationalized across four interrelated domains; stakeholder roles, residue reuse innovation, consumption behavior, and digital transformation.

Methodologically, the study applies:

- A PRISMA-based SLR with defined inclusion/exclusion criteria.
- A bibliometric analysis of 137 peer-reviewed articles (2000–2024) using VOSviewer.
- And a thematic framework guided by four key research questions that cut across environmental, technological, and market-driven domains.

By triangulating these methods, the study delivers:

- Conceptual novelty (a multi-pillar sustainability framework).
- Methodological innovation (a hybrid qualitative-bibliometric lens), and
- Practical value (relevant typologies and stakeholder mappings).

This positions our work as a strategic, system-oriented review that not only synthesizes fragmented literature but also identifies patterns, gaps, and leverage points for future sustainability transitions in the global coffee sector. The rest of the manuscript is organized as follows: in Section 2 explores the sustainability challenges and opportunities in the global coffee industry; Section 3 describes the methodological approach; Section 4 analyses the main results of the investigation. While Section 5 discusses the main opportunities and challenges of the coffee supply chain is discussed. Finally, Section 6 summarizes the main conclusions, and limitations encountered during the research.

2. Sustainability challenges and opportunities in the global coffee industry

This section frames the broader sustainability landscape within which the global coffee supply chain operates, establishing the strategic context for the study's four research questions and the need for an integrative literature review. The global coffee industry, valued at over $200 billion USD annually, ranks second after crude oil in trade volume [15–18]. Beyond its economic importance, coffee supports the livelihoods of over 125 million people globally, particularly smallholder farmers in equatorial and subtropical regions [19–21]. The industry has deep social and cultural relevance, playing a vital role in household income, foreign exchange earnings, and employment. However, the coffee supply chain is increasingly under pressure from converging sustainability risks, ranging from deforestation, soil erosion, water stress, and biodiversity loss to climate instability and socio-economic inequity [22–24]. Economic vulnerabilities are exacerbated by price volatility, while social challenges such as labor rights and gender equity remain persistent barriers to inclusive sustainability [25,26].

Technological disruption adds another layer of complexity. Innovations like blockchain-based traceability, IoT sensors for monitoring farm conditions, and digital certification platforms are reshaping governance and transparency in the supply chain [9]. Simultaneously, circular economy approaches, such as the reuse of spent coffee grounds (SCGs) and cascara, are emerging as promising but under-integrated solutions [27].

While numerous studies have addressed sustainability concerns individually, such as life cycle analysis [28] or SCG valorization [13], few have connected these themes completely across stakeholders, technologies, reuse strategies, and markets. This is further evidenced by the limited use of bibliometric tools to trace thematic shifts across time, geography, and disciplines. Notably, a recent review by Wright et al. [29] explores governance frameworks and certification schemes but stops short of a cross-sectoral reuse typology or bibliometric synthesis of innovation clusters. This highlights a conceptual and methodological gap that our study addresses.

In response, this study explores the following research questions:

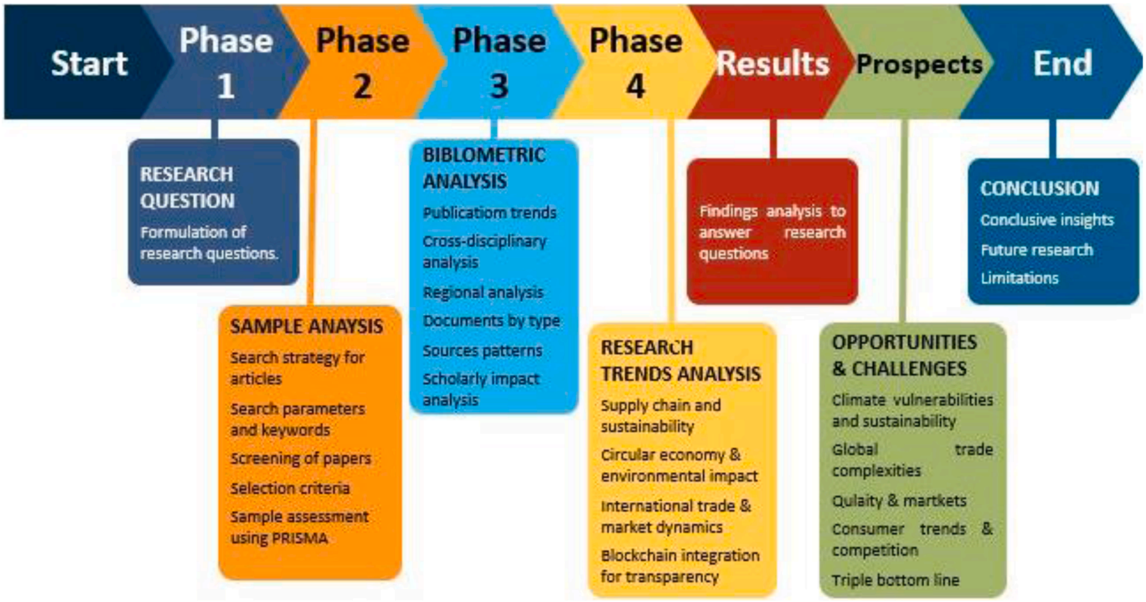

Fig. 1. Methodological framework of systematic literature review (SLR).

- × RQ1: Who are the main stakeholders in the current coffee supply chain and what roles do they play in the overall process?
- × RQ2: What innovations and opportunities can arise from the potential reuse of coffee residues in other sectors, such as agriculture, the cosmetics industry or energy production?
- × RQ3: How do coffee consumption trends influence the supply chain and what are the implications for target markets?
- × RQ4: How can digital innovation and digital technologies improve efficiency, traceability and sustainability in the coffee supply chain?

To explore these challenges, the following section synthesizes recent evidence around stakeholder roles, waste valorization, consumer dynamics, and technological disruption; four thematic pillars that structure the rest of this review. By doing so, we lay the foundation for an integrated understanding of sustainability in the coffee sector that goes beyond fragmented analyses found in previous literature.

The coffee supply chain includes key by-products and consumption patterns central to our analysis. SCGs generated at a ratio of ~650 kg per ton of green coffee offer valorization potential through composting, bioenergy, and material conversion. However, more than 90 % of these residues remain landfilled [30,27]. Cascara, or dried coffee cherry husks, is gaining traction in product innovation and dietary applications [31,32]. Meanwhile, regional consumption dynamics, particularly in Asia, Europe, and North America are reshaping demand patterns and traceability requirements [33].

Thus, the sustainability challenges and opportunities in the global coffee industry must be viewed through a system-level lens one that accounts for interlinked social, environmental, technological, and economic dimensions. This review, unlike prior studies, offers that integrated perspective while embedding it within a data-driven bibliometric foundation.

3. Materials and methods

This study utilized a systematic literature review methodology, following guidelines from "*Systematic Reviews in the Social Sciences: A Practical Guide*" by Petticrew and Roberts [34]. It comprehensively analyzed and mapped the coffee supply chain, incorporating scholarly works, industry reports, and reputable publications. The methodological approach is designed to ensure a thorough and unbiased exploration of supply chain dynamics. Important articles about the coffee supply chain were thoroughly searched for, adhering to specific inclusion criteria to capture relevant literature, with a primary focus on publications from the past decade. To identify relevant articles, academic databases such as PubMed, Scopus, and Web of Science were searched, along with databases specific to the coffee industry, such as the one provided by the International Coffee Organization (ICO). Specifically, bibliometric analyses were conducted to assess publication trends, journal contributions, and country profiles. The Scopus database was given preference for its comprehensive coverage of peer-reviewed literature in the social sciences, aligning with widely accepted scholarly practices. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol guided the review process, facilitating the identification and screening of literature. Initially, over 500 articles were found, but after careful examination of their titles, abstracts, and keywords, the selection was narrowed down to approximately 137. These selected articles underwent a detailed review, focusing on gathering essential information about stakeholders, their roles, challenges, opportunities, and the overall understanding of the coffee supply chain. This approach facilitated the systematic organization and analysis of data, providing a clear understanding of how the coffee supply chain operates. This Systematic Literature Review (SLR) is utilized to identify, evaluate, and synthesize existing research studies pertinent to the specific research questions. This combination of systematic review protocol (PRISMA), bibliometric co-occurrence analysis, keyword-based clustering, and multi-dimensional stakeholder and sectoral mapping constitutes a novel methodological framework not previously applied in coffee supply chain literature, thereby enhancing both analytical depth and reproducibility. Fig. 1 illustrates the primary phases undertaken to conduct the SLR.

3.1. Phase#1: formulation of research questions

In systematic literature reviews, the formulation of research questions is a critical step that defines the scope, analytical depth, and coherence of the investigation. In this study, the questions were developed following an iterative process comprising: (i) an exploratory scoping of the literature using PRISMA screening, and (ii) an initial bibliometric mapping using VOSviewer to identify underexplored linkages across themes. Based on this synthesis of structural and conceptual gaps, the following overarching question was derived to guide the study:

"How is sustainability in the global coffee supply chain evolving across stakeholder practices, innovation trajectories, and thematic

Table 1
Formulation and elaboration of research inquiries.

Research Questions	Gap Addressed and Analytical Intent
RQ1: Who are the main stakeholders in the current coffee supply chain and what roles do they play in the overall process?	Existing reviews mention actors in passing but lack a typology and functional classification. This question aims to extract a stakeholder-role matrix using co-occurrence and cluster analysis to classify actors and examine their influence, interactions, and governance roles.
RQ2: What innovations and opportunities can arise from the potential reuse of coffee residues in other sectors, such as agriculture, the cosmetics industry or energy production?	Despite growing interest in SCGs and cascara, prior studies lack cross-sectoral reuse classification. This question supports building a reuse taxonomy and exploring diffusion pathway for circular economy integration.
RQ3: How do coffee consumption trends influence the supply chain and what are the implications for target markets?	Demand-side sustainability is often underrepresented in system reviews. This study integrates consumption analytics with bibliometric mapping of regional and market-oriented themes to assess how consumer behavior reshapes demand, production, and sustainability practices.
RQ4: How can digital innovation and digital technologies improve efficiency, traceability and sustainability in the coffee supply chain?	This question aims to investigate, how technologies like blockchain, IoT, AI, and GIS contribute to making the coffee supply chain more transparent, efficient, and sustainable. While digitalization is often cited as a transformative force, existing literature lacks a consolidated view of its specific applications and their measurable impact on sustainability metrics (e.g., transparency, carbon reduction, cost efficiency, and ethical compliance). This research question therefore seeks to synthesize dispersed knowledge across these technological subdomains, identifying how such innovations can drive traceability, reduce environmental impact, and support ethical practices.

research priorities, and what integrated insights can be drawn to inform future system-level interventions?"

This framing prioritizes systems thinking and aims to bridge isolated strands of literature into a cohesive analytical framework. Building from this central question, we developed four targeted research questions, each aligned with a core sustainability dimension and mapped to specific literature blind spots. The research questions serve as organizing anchors for both the bibliometric analysis and the thematic synthesis. They are designed to span the full sustainability arc of the global coffee supply chain and to capture dynamic interdependencies across said dimensions as outlined in Table 1.

Together, these research questions form the analytical framework of the review. They were iteratively refined during full-text screening and data extraction and directly shape both the content synthesis and the bibliometric outputs presented in later sections. The long-term contribution of this framework is twofold: Conceptually, the framework integrates disparate themes into a cohesive, multi-pillar sustainability perspective. Practically, it equips industry stakeholders, policymakers, and researchers with actionable insights to identify leverage points, whether through improved collaboration, technological adoption, or circular practices, to drive sustainability transitions across the coffee value chain. The next phase outlines the inclusion and exclusion criteria used to construct the final corpus of 137 peer-reviewed articles, which forms the empirical basis of our analysis.

3.2. Phase#2: sample characterization for analysis

3.2.1. Search strategy of articles

To ensure a comprehensive literature review, careful selection of search platforms was conducted. A systematic search across academic databases, journals, conference proceedings, and other sources followed. An initial scoping analysis was conducted across major academic databases, including Scopus, Google scholar and Web of Science (WoS). This phase helped assess the thematic landscape and validate keyword relevance. While Google Scholar offers extensive coverage, concerns about data quality led us to prioritize Scopus. However, for the final systematic review and bibliometric analysis, we exclusively focused on Scopus. This decision was made due to Scopus's broad multidisciplinary coverage, structured metadata, and its integration with bibliometric tools such as VOSviewer, which was essential for our co-occurrence and thematic clustering. While WoS was referenced for historical context and to validate the initial keyword design, it was not used in the final article inclusion phase. Thus, the results presented are based solely on Scopus-indexed peer-reviewed literature. The search was narrowed down to peer-reviewed journals, with emphasis on "Articles", "Articles in press", and "Review articles" to maintain content quality and selection integrity.

3.2.2. Search parameters and keywords

The search strategy employed a combination of keywords relevant to the research topic. Scopus's Boolean syntax was utilized to refine search queries and retrieve more relevant results. Scopus, known for its expansive coverage, facilitates searches using Boolean syntax, enabling users to combine keywords using operators like AND, NOT, and OR for enhanced result relevance. Initially, our inquiry commenced with inclusive terms with general keywords such as " Coffee supply chain dynamics", " Stakeholder identification", "Supply chain roles analysis" and "Challenges and opportunities assessment" resulting in a set of documents from 2013 to 2023. structured as (TITLE-ABS-KEY (Coffee industry) AND TITLE-ABS-KEY (supply chain dynamics)). TITLE-ABS-KEY is a Scopus-specific search operator that restricts the query to terms found in the article's title, abstract, or author keywords, ensuring high thematic relevance. This helped filter out peripheral content and focus the review on studies where the coffee supply chain was a central topic. The scrutiny encompassed articles where the specified string appeared in the article title, abstract, or keywords. The preliminary analysis on Scopus initially identified 380 documents spanning the years 2000 to 2024.

The search is further fine-tuned by incorporating additional keywords, tailoring our approach to extract highly relevant articles. The keyword selection process is divided into two distinct steps. In the first step, the focus is on broader terms related to the coffee industry, such as "Coffee industry" combined with specific aspects like "supply chain dynamics", "stakeholder identification", "supply chain roles analysis", "challenges and opportunities assessment", "sustainability initiatives correlation", and "United Nations Sustainable Development Goals (SDGs)". These keywords encompass a wide range of topics within the coffee industry, allowing for a comprehensive exploration of various aspects. This initial step yielded a total of 312 papers across all keyword combinations. In contrast, the second step narrows down the focus to the specific domain of the coffee supply chain. Here, the search strings are tailored to capture nuances within the supply chain context, such as "Coffee supply chain" combined with keywords like "eco-friendly farming methods assessment", "ethical sourcing evaluation", "supply chain sustainability assessment", "environmental and social impact analysis", "consumer behavior study", "sustainable transformation analysis" and "resilience in supply chains". This step resulted in the retrieval of 69 papers. These keywords delve deeper into the intricacies of supply chain management within the coffee industry, offering a more granular exploration of relevant themes and issues. This refined investigation involved the incorporation of supplementary keywords, an

Table 2
Analysis of coffee supply chain keywords and retrieved papers.

Step	Keywords used for search	Papers retrieved
1st	(TITLE-ABS-KEY (Coffee industry) AND TITLE-ABS-KEY (supply chain dynamics))	12
	(TITLE-ABS-KEY (Coffee industry) AND TITLE-ABS-KEY (stakeholder))	75
	(TITLE-ABS-KEY (Coffee industry) AND TITLE-ABS-KEY (supply chain roles analysis))	137
	(TITLE-ABS-KEY (Coffee industry) AND TITLE-ABS-KEY (challenges and opportunities))	40
	(TITLE-ABS-KEY (Coffee industry) AND TITLE-ABS-KEY (sustainability initiatives))	25
	(TITLE-ABS-KEY (Coffee industry) AND TITLE-ABS-KEY (Sustainable Development Goals))	23
2nd	(TITLE-ABS-KEY (Coffee supply chain) AND TITLE-ABS-KEY (farming methods))	6
	(TITLE-ABS-KEY (Coffee supply chain) AND TITLE-ABS-KEY (transparent sourcing))	9
	(TITLE-ABS-KEY (Coffee supply chain) AND TITLE-ABS-KEY (supply chain sustainability assessment))	25
	(TITLE-ABS-KEY (Coffee supply chain) AND TITLE-ABS-KEY (environmental and social impact))	15
	(TITLE-ABS-KEY (Coffee supply chain) AND TITLE-ABS-KEY (consumer behavior))	8
	(TITLE-ABS-KEY (Coffee supply chain) AND TITLE-ABS-KEY (sustainable transformation))	6
Total		381

iterative process aimed at tailoring the search to our focused research interest. With these keywords the number of papers retrieved for each step, totaling **381** papers as shown in Table 2.

3.2.3. Screening of papers and identifying selection criteria

To ensure transparency and methodological rigor in the selection of articles, we employed three interlinked criteria: inclusion, exclusion, and eligibility.

- Inclusion criteria were defined to identify studies relevant to the coffee supply chain and sustainability, including peer-reviewed journal articles published between 2000 and 2024, written in English, and focusing on stakeholder roles, circular reuse of residues, digital innovation, and consumption trends.
- Exclusion criteria helped eliminate non-relevant or lower-quality materials, such as duplicates, editorials, book chapters, commentaries, or articles without accessible full texts.
- Eligibility criteria served as a refinement filter applied during the full-text screening stage, ensuring that retained studies not only matched the inclusion scope but also directly addressed one or more of the four core research questions. This step also confirmed whether a study contributed empirical or conceptual insights related to our analytical framework.

This three-tiered filtering process supports internal consistency and strengthens the review's reliability, distinguishing between general relevance (inclusion), disqualification conditions (exclusion), and final analytical suitability (eligibility) to best address the research objectives and contribute meaningfully to advancing knowledge in the field of coffee supply chain. Thus these criteria were identified and are summarized below

Exclusions Criteria

- EX1: Publications over 20 years old and non-authentic sources.
- EX2: Non-English language publications.
- EX3: Non-peer-reviewed sources like opinions, blogs, and news articles.
- EX4: Articles lacking empirical data or primary research findings.
- EX5: Studies focusing on theoretical frameworks unrelated to coffee sector challenges.

Inclusion Criteria: Before delving into specific eligibility criteria, it's essential to establish the overarching principles guiding article selection. Inclusion criteria set the stage for identifying articles that align with the research objectives and contribute meaningfully to the study.

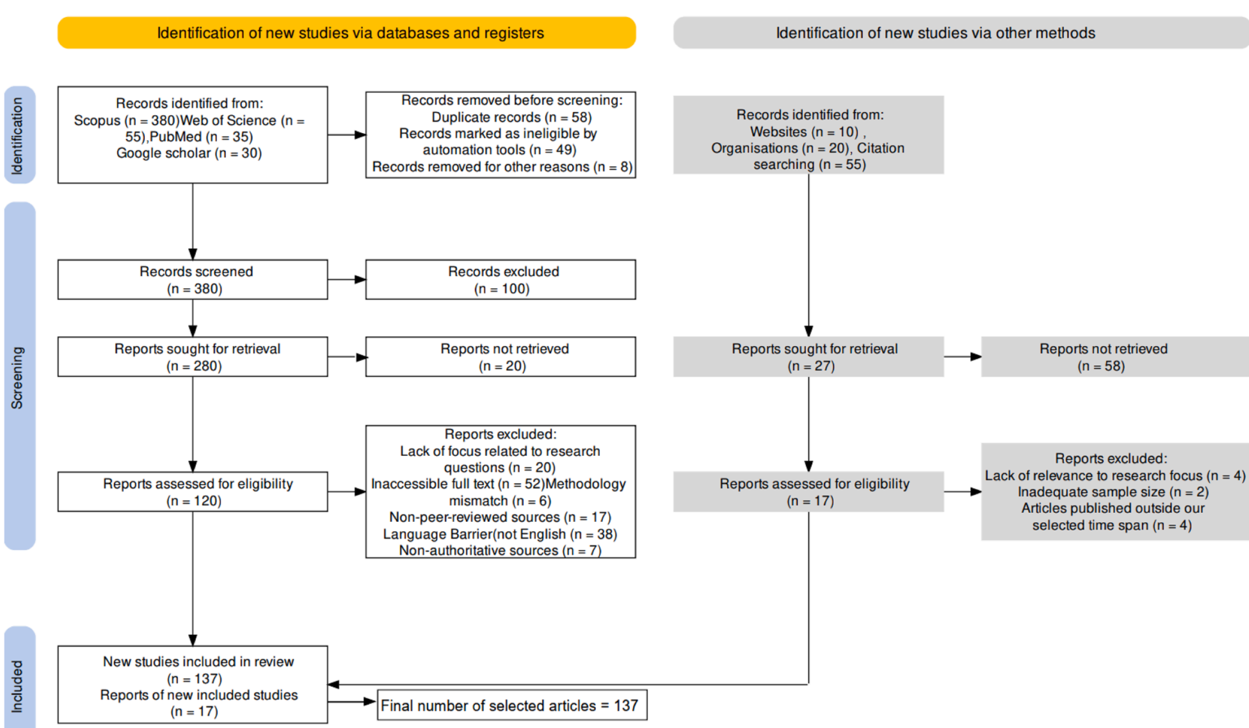

Fig. 2. PRISMA flowchart for systematic screening process of articles.

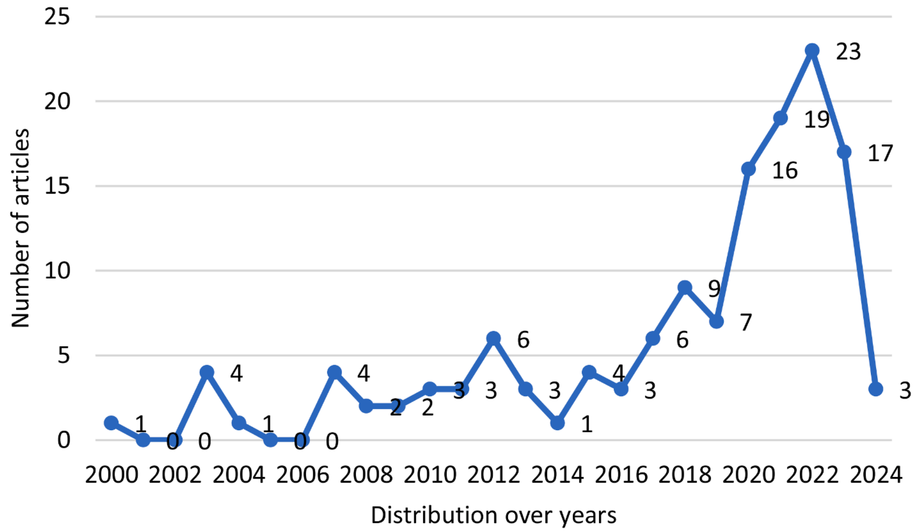

Fig. 3. Papers distribution over time (Source: Scopus).

- I1: Incorporate scholarly sources like journal articles, conference papers, and reviews
- I2: Articles addressing stakeholder roles, residue reuse innovations, consumption trend impacts, and digital technology applications in the coffee industry were included.
- I3: Articles containing keywords for coffee industry.
- I4: Studies exploring the role of government policies and incentives in coffee industry.
- I5. Research addressing the implications of digital innovation on operational practices and product traceability in coffee production and distribution.
- I6: Articles applying theories or technologies to address real-world challenges in the coffee supply chain.

Eligibility Criteria: In addition to inclusion criteria, eligibility criteria provide specific guidelines for determining the suitability of articles for inclusion in the review. These criteria encompass factors such as research methodology, clarity of findings, novelty of insights, and coverage of the coffee supply chain. By adhering to these criteria, the screening process aims to identify articles that meet rigorous standards of academic quality and relevance to the research objectives

- EL1: Articles relevant to sustainability challenges and dynamics in the coffee industry were included.
- EL2: Studies employing robust research methodologies, such as systematic literature reviews, empirical research, case studies, and quantitative or qualitative analyses, were considered eligible for inclusion.
- EL3: Clear and coherent findings aligning with research objectives were included for reliability.
- EL4: Articles offering novel insights or significant contributions to coffee supply chain knowledge were eligible.

3.2.4. Sample classification using PRISMA

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Protocol [35] was integrated into systematic literature review methodology to ensure a rigorous and transparent approach. PRISMA was selected due to its wide acceptance in interdisciplinary research and its capacity to ensure structured, reproducible, and unbiased article selection. This framework facilitated a standardized multi-step process involving identification, screening, eligibility assessment, and inclusion, as illustrated in Fig. 2. Compared to automated tools such as DistillerSR or EPPI-Reviewer, PRISMA provided greater flexibility and transparency, particularly in supporting custom classification schemes and integration with bibliometric mapping tools like VOSviewer. This enabled us to trace thematic intersections across environmental, technological, and governance-related domains while maintaining a robust audit trail. Only peer-reviewed, English-language sources were considered to maintain consistency and ensure quality in the interpretation and analysis aligning with the language proficiency of the author's team. After formulating the research questions and executing our search strategy in Scopus, the initial corpus comprised 1275 bibliographic records. Through de-duplication and exclusion of out-of-scope studies using predefined criteria, 775 documents were filtered out. The remaining 500 eligible articles were subjected to full-text screening, ultimately resulting in 137 studies (2000–May 2024) selected for detailed bibliometric and qualitative analysis.

3.3. Phase#3: bibliographic sampling

The study commenced with the use of VOSviewer software to construct bibliometric networks, vital for understanding the intricacies of the coffee supply chain. VOSviewer, a Java-based tool [36], facilitated connections between elements using metrics like co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation. Utilizing bibliographic data from sources like Scopus, VOSviewer generated networks [37] that were analyzed and clustered. Furthermore, trends were directly extracted and examined from Scopus, ensuring a thorough exploration of scholarly contributions. Fractional counting, employed in this study, aimed to reduce the impact of heavily authored documents, aligning with the study's focus on identifying key contributors and collaborations. This method adjusts co-authorship link strength based on document authorship, enhancing analysis precision [38]. Conversely, full counting treats each co-authorship link equally, disregarding authorship variations [39]. These techniques, combined with mapping and networking formulas, provided a comprehensive understanding of collaborative relationships and research impact within the scholarly landscape.

3.3.1. Publication trends over time

The line chart given in Fig. 3 depicts the distribution of published articles over time, spanning from 2000 to 2024 (may 2024). The temporal distribution reflects dynamic trends in research output over the specified period, suggesting varying levels of scholarly interest and engagement with the subject matter over time.

3.3.2. Cross disciplinary analysis

The distribution of articles according to subject area reveals a diverse

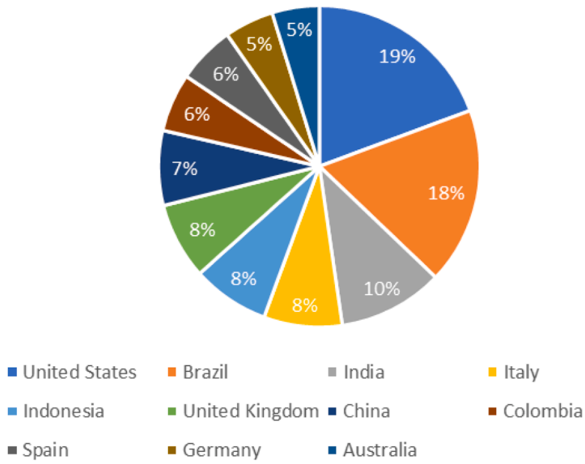

Fig. 4. Distribution of documents and authors by country in coffee industry (Source: Scopus).

landscape of research within the coffee industry. The survey pointed out that agricultural and biological sciences dominate with a significant share of 22.0 %, indicating a substantial focus on the ecological and agricultural aspects of coffee production. This emphasis underscores the industry's commitment to sustainable farming practices and environmental conservation. Engineering and environmental science follow closely, each contributing 12.2 % and 13.1 % respectively. This reflects the interdisciplinary nature of sustainability efforts in the coffee supply chain, where technological innovations play a crucial role in enhancing efficiency and reducing environmental impact. Business and management studies (7.5 %), social sciences (8.3 %), and chemistry (8.2 %) also make notable contributions. These disciplines highlight the multifaceted approach required to address sustainability challenges comprehensively, encompassing economic, social, and chemical aspects of coffee production and distribution. Moreover, fields like biochemistry (8.9 %), energy (6.0 %), and medicine (6.1 %) are gaining recognition, each contributing to the understanding of coffee's impact on human health and the importance of genetic research for crop improvement. This diverse distribution underscores the complexity of sustainability issues in the coffee industry and emphasizes the need for interdisciplinary collaboration to address them effectively.

3.3.3. *Regional analysis*

The distribution of papers by country demonstrates a global engagement with coffee industry research. Notably, the number of manuscripts published in United States (19 %), Brazil (18 %), India (10 %), Italy (8 %), and Indonesia (5 %), as shown In Fig. 4.

In this study, VOSviewer software was utilized to conduct a comprehensive analysis of regional data distribution across various countries, with a focus on identifying clusters based on co-occurrence patterns with additional data detailing country-specific metrics such as the number of documents, citations, and total link strength. The analysis encompassed a total of 67 items, with findings revealing the presence of five distinct clusters. These clusters showcased varying degrees of interconnectedness among countries, elucidating shared research interests and collaborative trends. Cluster 1 highlighted in red emerged as the largest, comprising 23 countries including Algeria, France, and the United States, among others, showcasing a diverse array of research collaborations with a collective document count of 798 and a total link strength of 12,336. Cluster 2, depicted in green, featured 18 countries such as Australia, Japan, and Sweden, indicating strong ties within certain regions or research domains with a combined document count of 474 and a total link strength of 6895. Cluster 3, represented in blue, comprising 14 countries like China, Pakistan, UAE and India, highlighted collaborations predominantly within the Asia-Pacific region with a total document count of 278 and a link strength of 5934. Cluster 4, in yellow, with 10 countries including Denmark, Hungry, and Norway, exhibited a unique regional focus, marked by a document count of 181 and a total link strength of 3644. Lastly, Cluster 5, shown in purple, consisted of only two countries, the Philippines and Taiwan, suggesting specialized collaborations with a combined document count of 9 and a total link strength of 87. These findings provide insights into the regional distribution of research activities and collaborative patterns among countries, shedding light on the dynamics shaping global research networks.

Our co-occurrence analysis given in Fig. 5 offers valuable insights into regional research patterns and underscores the importance of fostering international collaborations to advance knowledge and innovation across diverse domains. These findings contribute to a deeper understanding of global research dynamics and inform strategic decision-making in fostering cross-border partnerships and initiatives.

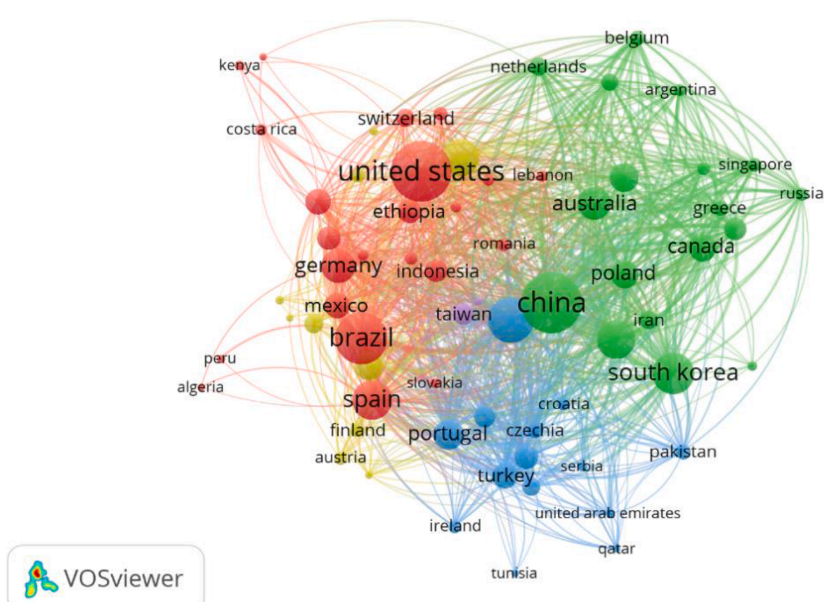

Fig. 5. Bibliographic coupling analysis depicts country co-occurrence patterns.

Table 3
Document metrics of top journals and sources in 2022.

Journal Name	Publisher	Cite Score 2022	SJR 2022	Source Documents 2022	Citations per year 2022	Review Articles % 2022
Journal of the Science of Food and Agriculture	Wiley	8.2	0.747	751	46,885	3.99 %
Sustainability (Switzerland)	MDPI	5.8	0.664	17,002	217,095	6.95 %
Food Chemistry	Elsevier	14.9	1.624	3008	236,007	3.99 %
Foods	MDPI	5.8	0.771	4105	41,517	10.82 %
Food Research International	Elsevier	12	1.36	1239	71,556	10.9 %
British Food Journal	Emerald Group Publishing	5.4	0.645	281	10,513	2.85 %
Journal of Cleaner Production	Elsevier	18.5	1.981	4799	329,579	7.27 %
Journal of Environmental Management	Elsevier	13.4	1.678	2384	110,922	8.52 %
Journal of Food Engineering	Elsevier	11.8	1.161	265	43,453	4.15 %
Journal of Food Science and Technology	Springer	6.5	0.666	489	26,899	5.93 %

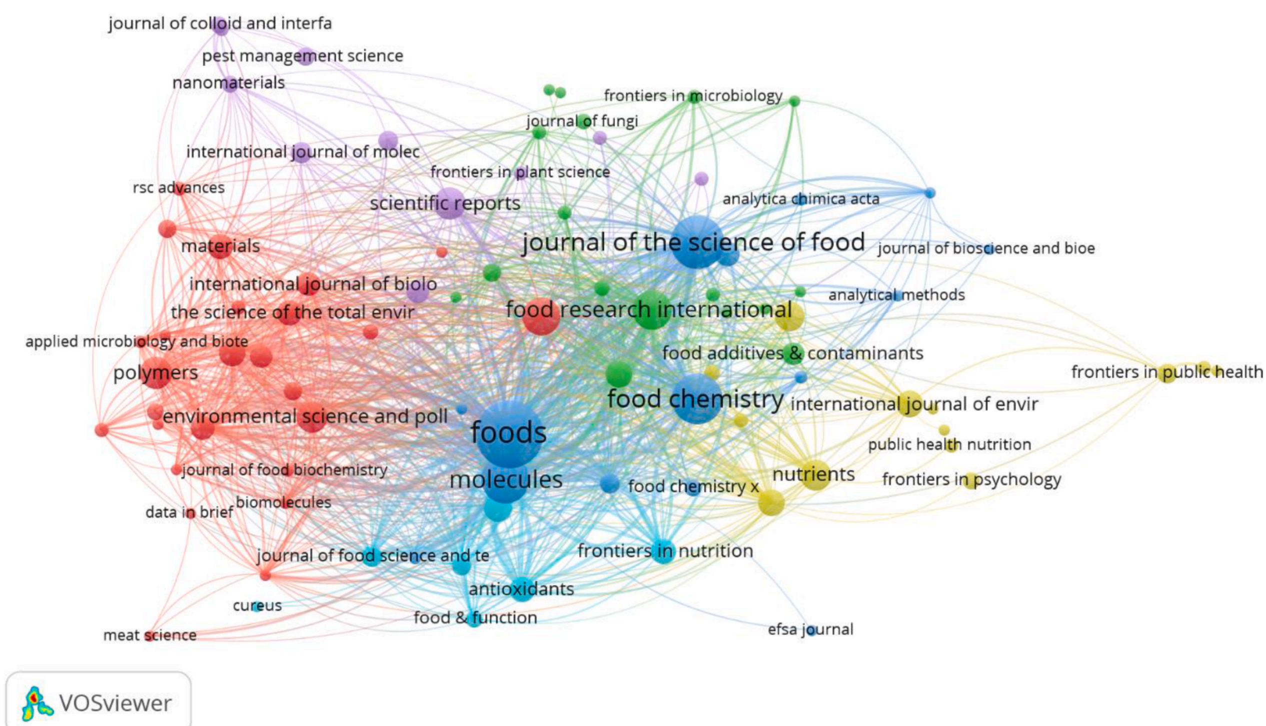

Fig. 6. Interdisciplinary Connections of scientific sources revealed through cluster analysis.

3.3.4. *Documents analysis by type*

Regarding the documents by type of publication the investigation pointed out the diversity in the types of publications contributing to coffee industry research, ranging from peer-reviewed articles comprising the majority at 66.3 % to conference papers (11.7 %), book chapters (8.3 %), reviews (8.0 %), books (1.9 %), conference reviews (1.3 %), notes (0.9 %), short surveys (0.7 %), editorials (0.4 %), letters (0.3 %), and other forms (0.2 %). Each type makes a distinct contribution to the breadth and depth of scholarly engagement in this field.

3.3.5. *Analysis of sources patterns across research fields*

Concerning the distribution by journal, it provides insights into the dissemination of coffee supply chain research across various academic journals, highlighting the key platforms where findings are published and contributing to the dissemination and exchange of knowledge within the scholarly community.

Table 3 provides an overview of document metrics for top journals and sources in the year 2022, extracted from the Scopus database. It includes key indicators such as the number of source documents, citations, SJR (SCImago Journal Rank), and the percentage of review articles published by each source. These metrics offer valuable insights into the scholarly output, impact, and editorial focus of leading journals across various fields, including food science, environmental management, and engineering. The data reflects the significant contributions made by these journals to the discourse on sustainability within the coffee supply chain.

The bibliographic coupling analysis in Fig. 6 reveals insightful patterns within a diverse array of scientific sources, offering a nuanced understanding of their interconnections and impact. The dataset, extracted from VOSviewer, encompasses 89 items distributed across six distinct clusters, connected by a total of 2584 links. Cluster 1 (red) stands out as the largest, comprising 26 items, followed by Cluster 2 (green) with 17 items, and Cluster 3 (blue) with 15 items. Clusters 4 (yellow), 5 (purple), and 6 (aqua blue) exhibit progressively smaller sizes, containing 13, 11, and 7 items respectively. Noteworthy sources such as "Food Chemistry," "Journal of Food Science and Technology," and "Journal of Agricultural and Food Chemistry" emerge as prominent nodes within the network, reflecting their significant influence and interconnectedness within the scholarly landscape. This analysis underscores the intricate relationships and collaborative dynamics shaping

Table 4
Top research authors contributions according to citation criteria in the field of coffee industry.

S. R	Authors	Title	Year	Citations	FWCI	Journal
1	Hejna	Potential applications of by-products from the coffee industry in polymer technology –current state and perspective	2021	42	933	Waste Management
2	Y. Lee et al.	Value-added products from coffee waste: a review	2023	16	490	Molecules
3	Peixoto et al.	Sustainability issues along the coffee chain: from the field to the cup	2022	11	503	Comprehensive Reviews in Food Science and Food Safety
4	Andrade et al.	Bioactive compounds and antioxidant activity from spent coffee grounds as a powerful approach for its valorization	2022	20	171	Molecules
5	Williams et al.	Does coffee have terroir and how should it be assessed?	2022	10	54	Foods
6	Franca and Oliveira	Potential uses of spent coffee grounds in the food industry	2022	18	271	Foods
7	Atabani, Mahmoud, et al.	Emerging potential of spent coffee ground valorization for fuel pellet production in a biorefinery	2022	17	198	Environment, Development and Sustainability
8	Gebreeyessus	Towards the sustainable and circular bioeconomy: insights on spent coffee grounds valorization	2022	28	210	The Science of the Total Environment
9	Durán-Aranguren et al.	Scientometric overview of coffee by-products and their applications	2021	21	372	Molecules
10	De Bomfim et al.	Valorization of spent coffee grounds as precursors for biopolymers and composite production	2022	22	261	Polymers

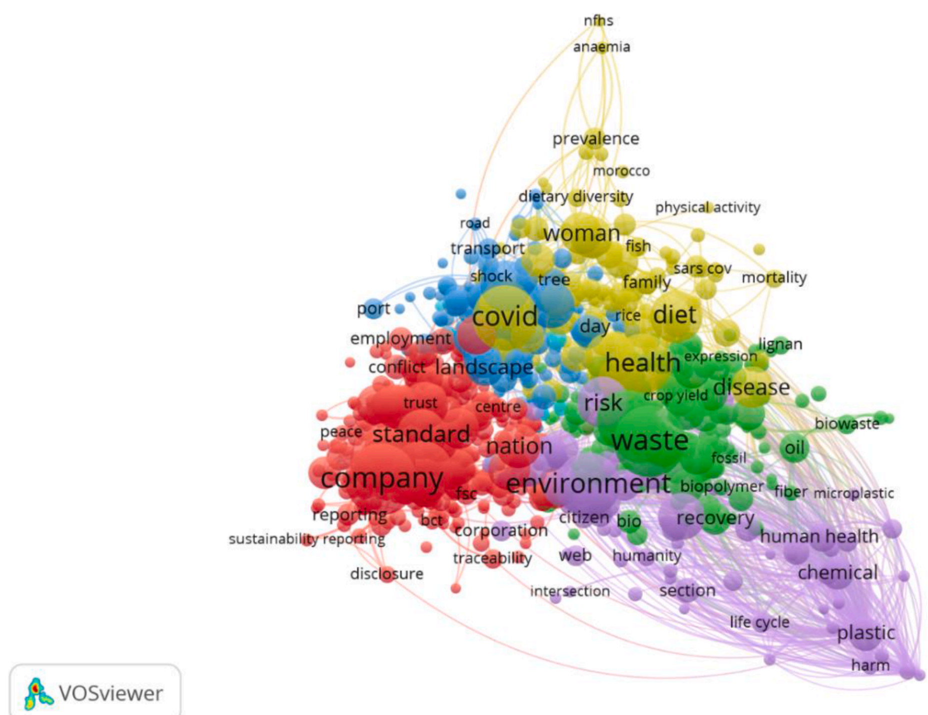

Fig. 7. Co-occurrence analysis of titles and abstracts mapping the research domain of the coffee supply chain.

research in fields spanning food science, environmental health, and biotechnology.

3.3.6. Scholarly research impact assessment for coffee industry

synthesizes notable contributions in coffee industry research, assessing their scholarly impact through citation counts in Scopus and Field-Weighted Citation Impact (FWCI) from SciVal. FWCI, normalized for publication year, document type, and disciplinary variations, offers insights into citation impact. Articles with FWCI > 1.00 indicate above-average citation rates. For instance, Hejna et al.'s [13] exploration of by-products' potential in polymer technology garnered 42 citations, with an impressive FWCI of 933, denoting substantial influence. Similarly, Gebreeyessus [12] provided insights into sustainable bioeconomy, with 28 citations and an FWCI of 210, indicating notable scholarly impact. This evaluation clarifies the diverse scholarly landscape within the coffee industry, offering insights into research relevance and influence across different thematic areas and methodologies. Table 4 summarizes the top research authors contributions according to citation criteria in the field of coffee industry.

3.4. Phase# 4: research trends analysis

In this section, the research delved into a co-occurrence analysis of titles and abstracts to map research landscape of the complete coffee supply chain. Through the utilization of bibliometric methods, the primary objective was to identify the key research fields within this domain. Initially, all title fields from the selected papers were considered, with a minimum occurrence threshold set at 1. In total, this analysis encompassed 904 items, clustered into 6 distinct groups, with a total of 79,575 links identified among them. The cumulative link strength across these connections amounted to 394,965. Network visualization (Fig. 7) was employed to illustrate the co-occurrence

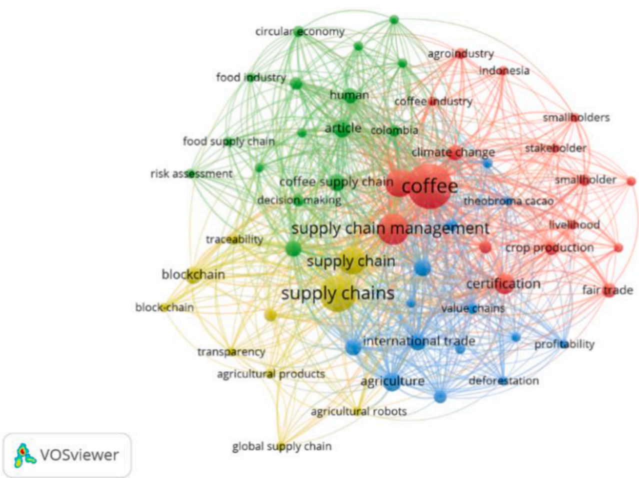

Fig. 8. Co-occurrence analysis of keywords.

relationships among items, where node size denoted frequency of occurrence and lines symbolized connections. This analysis revealed a modular network comprising 6 distinct clusters, each representing a coherent set of keywords with interrelated themes. Bibliometric clusters identified several key thematic groups differentiated by color, as illustrated in Fig. 7. In this figure, blue nodes represent environmental sustainability themes, green nodes highlight technological innovations, and red nodes indicate socio-economic research areas.

To refine our focus, clusters were narrowed down by increasing the frequency threshold to 8, with a specific emphasis on keywords related to the coffee supply chain. This refinement allowed us to delve deeper into the intersection of technology integration and sustainable coffee production as shown in Fig. 8. Fig. 8 visualizes the co-occurrence network where colors correspond to specific research domains as discussed below. Consequently, the overarching framework outlined earlier guided our exploration of this specific domain, enabling a more targeted investigation into the role of technology in enhancing transparency, traceability, and sustainability within the coffee supply chain.

By incorporating this additional refinement, our analysis gained further depth and specificity, enriching our understanding of the research within the coffee supply chain context. The VOSviewer software was employed to scrutinize bibliographic data encompassing scientific literature, comprising keywords and citations, and to construct co-occurrence networks of significant terms. Within this analysis, the occurrence attribute of keywords denotes the frequency of their appearance across documents. Additionally, the node size visually represents the frequency of a specific keyword, with larger nodes indicating higher occurrence rates. The connections between nodes illustrate shared occurrences between keywords, where the thickness and proximity of these lines signify the strength and frequency of co-occurrence across publications. Thus, closer proximity and thicker lines denote stronger relationships. The coloration of each cluster is determined by a complex scoring system considering occurrences, links, and link strength, ranging from purple (indicating very low scores) to yellow (indicating high scores). This analysis yielded 3140 keywords, with "coffee" emerging as the most cited term. Notably, the maximum frequency calculated by VOSviewer was 133. Among 47 keywords with frequencies of at least 8, a co-occurrence analysis was conducted, resulting in 4 clusters, 748 links, and 2165 link strength. Furthermore, the keyword "coffee" exhibited the highest total link strength (498), followed by "supply chains" (337) and "sustainability" (246).

3.4.1. Red cluster: supply chain and sustainability

Red Cluster stands out prominently within the bibliographic coupling network, indicating its significance in coffee supply chain management and sustainability research with total 16 items presented in Table 5. This cluster encompasses a diverse range of studies focused on various aspects such as agricultural production [40], agroindustry [41], certification [42], climate change [43], and the broader coffee supply chain dynamics as shown in Table 6. Scholarly contributions within this cluster emphasize the pivotal role of sustainable practices, exemplified by the study of Pancsira [44] about fair-trade principles that the global coffee trade has grown steadily since 2000, with fairtrade, coffee sustainability, and various forms of regulation being important topics in the post-World War II period. Since then, scientific publications on fairtrade, sustainability, value chains, and regulation increased steadily. Research by Dietz et al. [45] emphasizes the socio-economic implications of fair-trade certification for smallholder coffee farmers, underscoring its potential to enhance livelihoods and foster equitable value distribution. Moreover, the work of Voltolini et al. [46] examines the adoption of sustainable agricultural practices within coffee agroindustry, highlighting its significance in mitigating environmental degradation and promoting long-term sustainability. The discussion also covers importance of certification, with studies such as Valenciano-Salazar et al. [47] exploring the efficacy of certification schemes in ensuring ethical and environmentally responsible practices across coffee supply chains. Additionally, the impact of climate change on coffee production and supply chain resilience is studied in depth, as evidenced by the research conducted by Tamburini et al. [48], which underscores the need for adaptive strategies such as crop diversification and water conservation measures to mitigate the adverse effects of changing climatic conditions including increased frequency of droughts, erratic rainfall patterns, and rising temperatures. For the successful implementation of these

Table 5
Frequency and overall linkage potency of keywords within the red cluster.

Cluster red (16 items)			
Keyword	***Links***	***Total link strength***	***Occurrences***
Agricultural production	29	50	14
Agroindustry	23	43	11
Certification	45	150	35
Climate change	38	93	21
Coffee	56	498	154
Coffee industry	19	24	9
Crop production	32	75	16
Fair trade	19	43	18
Indonesia	17	32	8
Livelihood	20	39	8
Research	15	27	8
Smallholder	26	55	13
Stakeholder	19	33	8
Supply chain management	53	226	80
Sustainability	52	246	62
Value chain	13	17	9

Table 6
Frequency and overall linkage potency of keywords within the green cluster.

Cluster green (13 items)			
Keyword	***Links***	***Total link strength***	***Occurrences***
Article	39	126	27
Circular economy	23	45	11
Coffee supply chain	34	67	24
Colombia	29	60	13
Decision making	26	49	13
Environmental impact	24	46	9
Food supply chain	19	29	9
Human	37	108	21
Life cycle	24	43	8
Life cycle assessment	20	36	8
Optimization	26	62	14
Priority journal	23	44	8
Risk assessment	15	24	8

Table 7
Frequency and overall linkage potency of keywords within the blue cluster.

Cluster blue (10 items)			
Keyword	*Links*	*Total link strength*	*Occurrences*
Agriculture	38	124	29
Brazil	27	42	13
Deforestation	21	30	8
Developing countries	15	26	10
Governance	20	32	8
International trade	39	99	26
Marketing	30	63	15
Profitability	22	40	9
Sustainable development	41	128	26
Value chains	28	50	11

Table 8
Frequency and overall linkage potency of keywords within the yellow cluster.

Cluster yellow (8 items)			
Keyword	*Links*	*Total link strength*	*Occurrences*
Agricultural products	19	33	8
Agricultural robots	21	37	9
Blockchain	24	83	24
Costs	25	54	15
Global supply chain	13	22	8
Supply chains	54	337	105
Traceability	21	51	11
Transparency	21	37	9

sustainable practices, stakeholder engagement is essential, stakeholders are key players to support sustainability adoption and improving social and environmental performances across supply chain, the study by Journeault et al. [49] underscores into the role of diverse stakeholders in driving sustainability initiatives and fostering collaboration across value chain actors. Furthermore coffee-producing countries like Indonesia, examined, with research by [50] shedding light on the socio-economic and environmental dimensions of coffee production in the Indonesian context.

3.4.2. *Green cluster: circular economy and environmental impact*

Green cluster, emerges as a pivotal node within our systematic investigation, revealing a detailed discussion about the circular economy concept and its environmental implications within the coffee industry. This group thoroughly examines important topics like circular economy ideas, evaluating environmental effects, and making decisions covering around 13 different items given in Table 6. This discussion focuses on the circular economy, emphasizing how its principles are used in the coffee industry. Scholars like Mazzi and Ren [51], Zhao et al. [52] and Hellweg and Canals [53] have studied closely the transformative potential of circular economy practices in fostering resource efficiency, waste reduction, and sustainable value creation. The discussion by Sakamoto et al. [54], Hicks [55] and extends to examine how coffee production and supply chain activities affect the environment, with a specific emphasis on evaluating and addressing their environmental impact. Enhancing management techniques in farming and fertilization stands out as crucial for minimizing greenhouse gas emissions. Optimizing irrigation emerges as the primary strategy to mitigate the impacts of water scarcity. Study conducted by Usva et al. [56] provide valuable understanding into the life cycle assessment of coffee production, explaining the environmental hotspots and mitigation strategies within the coffee supply chain. Furthermore, Salvador et al. [57] specifies the integration of life cycle assessment methodologies facilitates informed decision-making processes aimed at optimizing resource utilization and minimizing environmental footprints. In parallel, by examining the interplay between human factors, risk perceptions, and optimization models, these studies contribute to a deeper understanding of sustainable decision-making processes within the coffee industry. These diverse perspectives pave the way for informed strategies aimed at advancing sustainability goals.

3.4.3. *Blue cluster: international trade and market dynamics*

The Blue cluster containing 10 items depicted in Table 7, focuses on international trade and market dynamics in the coffee industry. It explores various aspects such as agriculture's role, market dynamics in countries like Brazil, and the impact of international trade on value chains and profitability. Sachs et al. [58] and Koning et al. [59] contributes into the interplay between governance structures, sustainable development goals, and market forces within the coffee industry. Additionally, studies by Etana [60] and Mutolib et al. [61] examine the impact of deforestation and agricultural practices on the environment, highlighting the importance of sustainable land management practices. Furthermore, the discussion extends to value chains and marketing strategies, with research by [62] about optimizing value chain efficiency and enhancing market competitiveness which suggests that big data and modern tech enhance the coffee supply chain, trimming costs and time, ensuring sustainable growth. Digital transformation improves efficiency, satisfaction, and profits, benefiting all stakeholders. By synthesizing these diverse perspectives, blue cluster highlights how international trade, market factors, and sustainability interact in the worldwide coffee industry.

3.4.4. *Yellow cluster: blockchain integration for enhanced transparency*

The Yellow cluster, labeled as Blockchain integration for enhanced transparency shown in Table 8, delves into the transformative impact of blockchain technology on supply chain operations using distributed digital ledger. Researchers have extensively examined the advantages of blockchain, emphasizing its role in ensuring transparency, traceability, and security across various industries. Studies by Hastig and Sodhi [63] and Saberi et al. [64] highlight the potential of blockchain in supply chain traceability, particularly in sectors like mining and pharmaceuticals. Besides, scholars such as Kamble et al., [65], Choi & Luo [66] and Parmentola et al. [67] have critically analyzed the application of blockchain in supply chain management and smart contracts in streamlining operations and accelerates payment procedures according to customer preferences. The integration of blockchain technology is shown to enhance cooperation among industry stakeholders, reduce inefficiencies, and promote environmental sustainability [68,69]. Additionally, blockchain facilitates real-time data exchange, optimizing supply chain performance and operational costs [70]. The utilization of smart contracts further streamlines logistics structures, particularly in multi-modal supply chains [71]. Fundamentally, the yellow cluster emphasizes the crucial role of blockchain integration in advancing transparency and efficiency within global supply chains.

4. Results and discussion

This section presents the findings of a structured analysis of 137 Scopus-indexed articles selected via the PRISMA protocol. A dual-method approach was employed: bibliometric clustering to map thematic densities and gaps, and qualitative synthesis aligned with four research questions. These approaches were triangulated to generate targeted insights into stakeholder dynamics, reuse innovations, consumer-driven trends, and digital transformation within the coffee supply chain. The bibliometric clusters identified in the methods section provided a structural foundation for recognizing dominant and under-explored themes, while the qualitative coding enabled targeted analysis of evidence aligned with each research question. Each results subsection directly corresponds to one research question, structured to progressively examine: (RQ1), to identifying untapped potentials for residue reuse (RQ2), to evaluating consumer trends shaping market practices (RQ3), and finally, to assessing the transformative role of digital innovations (RQ4). This design enables a multi-layered understanding of the interactions between actors, technologies, and market forces across

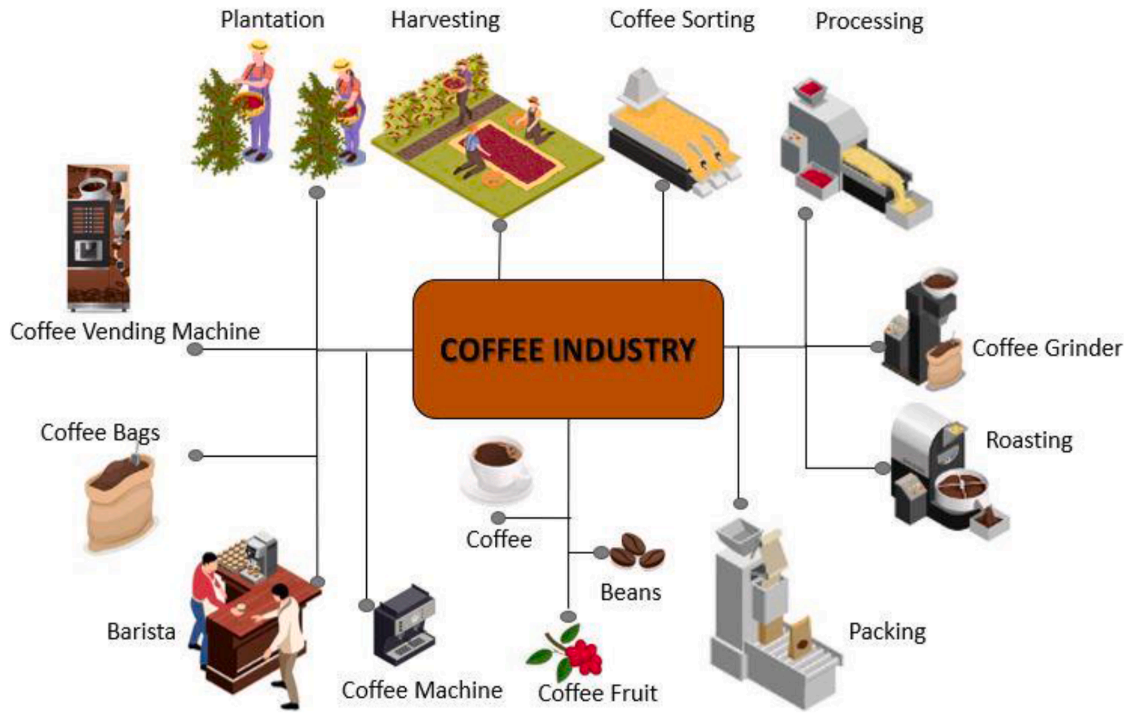

Fig. 9. Comprehensive industry and key players at a glance (source: Author's elaboration).

the value chain. A key contribution of this study lies in bridging fragmented research domains, particularly linking digital adoption with circular reuse models, thereby offering a cohesive systems perspective on sustainability that are underrepresented in prior reviews. These findings respond to previously identified literature gaps and contribute to broader sustainability dialogues, including alignment with the UN Sustainable Development Goals (SDGs). The following subsections elaborate on these insights and their implications for shaping a resilient, inclusive, and sustainable global coffee sector.

4.1. RQ1: who are the main stakeholders in the current coffee supply chain and what roles do they play in the overall process?

Analyzing RQ1, key stakeholders were identified and classified based on their roles within the coffee supply chain. The Coffee Supply Chain (CSC) orchestrates cultivation, processing, distribution, and consumption globally [72,73]. This network involves diverse stakeholders, from growers to consumers [74].

Fig. 9 illustrates the central role of the coffee industry surrounded by key components of the coffee supply chain. Beginning with harvesting and processing coffee fruit, beans are sorted, roasted, and packed. Coffee

Fig. 10. Comprehensive representation of coffee supply chain management flows as derived from the findings of RQ1 (source: Author's elaboration).

Fig. 11. Diverse applications of coffee residues beyond coffee production designed in response to RQ2 (source: Author's elaboration).

vending machines and coffee machines represent distribution and consumption points, while baristas serve as integral participants in the coffee experience.

Growers face challenges like climate vulnerabilities and market volatility [75–77], with initiatives promoting sustainable farming offering them avenues for empowerment and improved yield [78–80]. Exporters and importers navigate global trade complexities, while collaborative efforts streamline trade and expand market reach [81–84]. Roasters and manufacturers adapt to evolving preferences, while retailers explore personalized experiences and sustainability initiatives [85–87]. Consumer preferences significantly influence the supply chain, driving demands for ethical sourcing and sustainability [88–90]. This intricate system encompasses various players, from growers to retailers, catering to consumer demands worldwide [91–93].The dynamics within the coffee supply chain involve not only physical bean movement but also economic, social, and environmental interactions influenced by factors like trade relationships, sustainability practices, market fluctuations, and consumer preferences [94,95]. These stakeholders collaborate to ensure the efficient functioning of the supply chain while addressing sustainability concerns and market demands. Fig. 10 illustrates the coffee supply chain's comprehensive management, depicting the journey of coffee beans through different flows.

In physical flows coffee beans undergo processing, drying, and packaging before moving through trade points for quality checks and pricing [96–98]. Processing stages included in physical flows, such as wet [99] or dry methods [100,101], impart unique flavors [102]. In the industrial flow, packaged beans are transported to dry mills for sorting and testing, then to warehouses. Logistics in industrial flow ensure timely delivery of green beans to roasting facilities worldwide [103]. It also evaluates desiccants' effectiveness in preserving optimal moisture levels and sensory quality during storage [104]. Roasting transforms green beans into aromatic brown beans, altering their chemical composition [105]. The information flow manages distribution to retailers, encompassing marketing, sales, and customer service activities, alongside import and export processes [106].

Table 9
Potential reuse opportunities, possible markets, and digital technology benefits across various sectors.

Sector	Potential Reuse	Possible Market	Possible Digital Technology Benefits
Agriculture	Organic fertilizers Animal feed	Agricultural industry Livestock industry	IoT, GPS, remote sensing and data analytics
Cosmetics	Skincare formulations	Beauty brands Spa Cosmetics	Biotechnology Nanotechnology AI
Energy	Anaerobic digestion Biomass combustion	Energy sector Renewable energy industry	Energy management systems Process automation Biogas technology
Agriculture	Composting	Waste management facilities Composting facilities Organic waste processors	RFID tags GPS Recycling technology
Construction	Repurposing construction materials	Construction industry	Material science Recycling technology
Food	Culinary applications	Food industry Quality Control	Computational modeling Sensory analysis techniques
Pharmaceutical	Pharmaceutical formulations	Pharmaceutical industry	Drug formulation software

4.2. RQ2: what innovations and opportunities can arise from the potential reuse of coffee residues in other sectors, such as agriculture, the cosmetics industry, construction, food, pharmaceutical or energy production?

Research addressing RQ2 explores the diverse reuse potentials of coffee residues across sectors beyond coffee production. These applications of SCGs are given in Fig. 11. In agriculture, SCGs are increasingly valorized for their high nitrogen, phosphorus, and potassium content, serving as effective organic fertilizers and soil enhancers. Studies demonstrate that SCG compost enhances microbial activity and crop yields, making it a viable solution for low-input farming systems [107,108]. SCGs have also been trialed as livestock feed, particularly in regions facing feed shortages, though concerns remain around digestibility and toxicity, necessitating further research.

In the cosmetics industry, bioactive compounds such as polyphenols, tocopherols, and caffeine derived from SCGs exhibit antioxidant, anti-inflammatory, and exfoliating properties. These are being incorporated into formulations for scrubs, anti-aging creams, and shampoos, offering a sustainable alternative to synthetic ingredients [109,110]. For example, coffee-based scrubs produced using SCG extracts have shown comparable efficacy to conventional products, reducing environmental impact by replacing plastic microbeads.

The energy sector offers one of the most promising routes for large-scale SCG reuse. Pyrolysis, anaerobic digestion, and pelletization techniques enable SCG conversion into bio-oil, biogas, and solid fuel. Studies estimate that one ton of SCGs can yield over 300 liters of bio-oil or generate up to 25 GJ of energy when pelletized [111]. Hossain et al. [112]; Rijo et al. [14] and Ktori et al. [113] explores coffee waste's potential as a renewable energy source through biomass combustion and

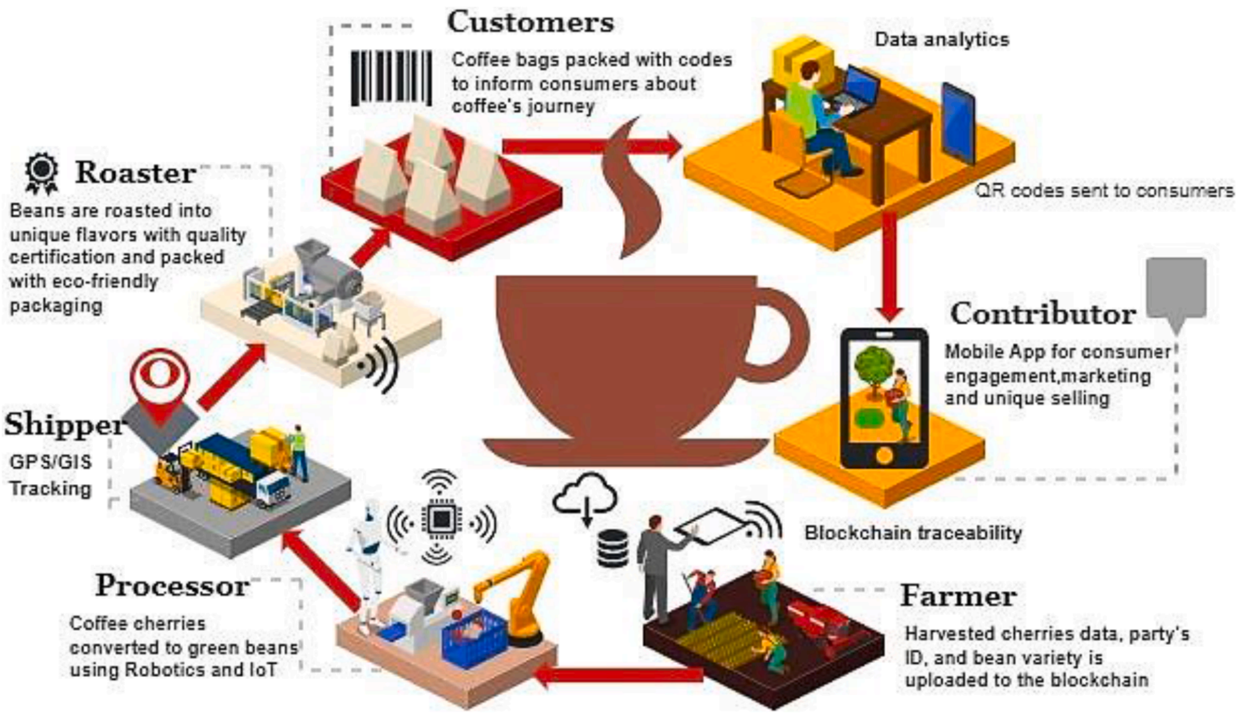

Fig. 12. Integration of digital technologies in the coffee supply chain to address RQ3, enhancing transparency, efficiency, and sustainability (source: Author's elaboration).

anaerobic digestion, mitigating energy shortages and reducing fossil fuel dependence. However, the economic feasibility remains constrained by infrastructure limitations and scale-up costs, particularly in developing countries.

In the construction industry, SCGs are being integrated into composite materials such as eco-concrete and bio-based polymers. These applications contribute to reducing carbon footprints and leveraging circular economy principles. Similarly, in the food industry, SCGs have been explored as flavor enhancers and additives in bakery products and meat analogs, offering both nutritional and sensory benefits. Regulatory approval and consumer perception, however, remain barriers to commercial adoption [114–117].

In pharmaceuticals, coffee residues have demonstrated potential in drug delivery systems and as natural antioxidants in formulations. Preliminary studies are evaluating the encapsulation of active compounds derived from SCGs in nanoemulsions and liposomes for dermatological and anti-cancer applications [118].

Despite these opportunities, key challenges include inconsistent quality of residues, processing costs, regulatory hurdles, and lack of industry-wide standards. Integration of digital technologies (e.g., blockchain for residue traceability or AI for residue sorting) can further support efficient valorization pathways. However, realizing these opportunities at scale requires multi-sectoral collaboration, supportive regulation, and technological investments to overcome adoption barriers and ensure safety, quality, and economic viability.

Collectively, these scientific inquiries underscore the multifaceted benefits of repurposing coffee residues, fostering a sustainable and circular economy paradigm. Table 9 provides a detailed breakdown of reuse opportunities, markets, and digital technology benefits across sectors and practical applications of coffee byproducts.

4.3. RQ3: how do coffee consumption trends influence the supply chain and what are the implications for target markets?

Recent shifts in coffee consumption patterns are significantly reshaping the structure and behavior of the coffee supply chain. Consumers are increasingly prioritizing sustainability, transparency, origin specificity, and ethical sourcing in their purchasing decisions [119]. Surveys indicate that over 60 % of consumers in North America and Europe prefer coffee certified as organic, Fair Trade, or Rainforest Alliance, and are willing to pay a premium for traceable, single-origin products [120,121]. This shift in demand towards sustainability and quality drives changes in production processes, including the adoption of organic farming methods [122,123], fair trade certifications [124], and traceability measures [125]. Producers are adopting organic and shade-grown practices to meet growing demand, especially in export-oriented countries like Ethiopia, Colombia, and Vietnam. Simultaneously, exporters and roasters are investing in direct trade partnerships, which eliminate intermediaries and provide consumers with greater visibility into farm-level practices, improving profit margins for smallholders.

The digitalization of supply chains is a major response to this trend. Platforms like Farmer Connect and IBM Food Trust are utilizing blockchain to enable QR code-based traceability, allowing consumers to scan and view the entire journey of their coffee, down to the farmer who harvested it. E-commerce platforms are leveraging AI to provide personalized product recommendations, and loyalty apps by companies like Starbucks and Nespresso reinforce sustainable brand loyalty.

Regionally, consumption trends vary. While Europe emphasizes ethical sourcing and environmental impact, Asia-Pacific markets (especially Japan and South Korea) show increased interest in quality, brewing innovations, and flavor differentiation. North American consumers exhibit the strongest trend toward transparency, subscription models, and third-wave coffee culture, reshaping logistics and marketing strategies [126].

These evolving preferences impose both opportunities and pressures on the supply chain. Retailers and roasters must adjust to shorter product cycles, transparent labeling, and digital consumer engagement. Increased demand for sustainability leads to cost burdens for smallholder farmers, who must comply with complex certification systems to access premium markets. Without adequate support, this may exacerbate inequity across the value chain. Overall, the influence of

Table 10
Sustainability's influence on coffee industry supply chains, markets, strategies, positioning, and competitiveness.

Influence on Supply Chain	Implications for Target Markets	Adaptation Strategies	Market Positioning	Competitive Market
Demand for sustainable products	Ethical and eco- friendly product	GIS GPS Remote sensing Organic farming	Sustainability certifications Eco-friendly branding	USDA Organic Shade-grown Bird-friendly certifications
Transparency and traceability	Informed sourcing, processing, and supply chain	Blockchain technology RFID tracking IoT	Market campaigns	Nespresso Starbucks
Fair trade products	Fair compensation Ethical treatment	Fair Trade UTZ Direct Trade certifications	Socially responsible brand	Fair trade certifications
Shift in consumer preferences	Ethical coffee	Marketing strategies Educational campaigns Certifications	Certified B Corporation Transparency initiatives	Packaging designs Advertisements Websites Social media Flyers In store displays
Transition to eco-friendly practices	Minimal environmental impact	Eco-friendly packaging Carbon-neutral production	Carbon offset programs Brand identity Messaging Unique selling propositions (USPs)	Product differentiation Pricing strategies Marketing Environmental initiatives
Quality and flavor differentiation	Unique flavor profiles High-quality products	Quality control Sensory analysis Chromatography	Unique flavors Single-origin sourcing Quality certifications	Reputation Flavor complexity Specialty coffee brands

consumption trends is profound, extending from production practices to packaging, branding, and logistics. The coffee supply chain must evolve by integrating digital tools, building transparent sourcing networks, and adapting to niche consumer segments, all while ensuring equitable and inclusive development for producers worldwide. Fig. 12 showcases the varied applications of digital technologies in the coffee supply chain, demonstrating their positive effects on production practices, supply chain management, and consumer engagement.

Table 10 provides a structured overview of sustainability's impact on the coffee industry, reflecting evolving consumer preferences and market trends. However, these changes also pose challenges, such as increased production costs associated with sustainable farming practices and the need for supply chain transparency [127]. Nonetheless, embracing these trends presents new market opportunities, such as niche segments ([121];) for specialty and single-origin coffees, as well as the potential for differentiation and premiumization in competitive markets [128,129]. Key coffee-exporting nations such as Brazil, Vietnam, Colombia, Ethiopia, and Honduras play pivotal roles in global coffee trade, with Brazil, as the world's largest producer and exporter, leading the way [130].

4.4. *RQ4: how can digital innovation and digital technologies improve efficiency, traceability and sustainability in the coffee supply chain?*

To address research question 4, which focuses on leveraging digital innovation and technologies to enhance efficiency, traceability, and sustainability in the coffee supply chain, significant strides have been made through technological advancements. One pivotal advancement is the integration of blockchain technology [131], offering a decentralized and transparent transaction recording system [132,133]. This integration promises heightened traceability and transparency within the web of the coffee supply chain [134–136], allowing stakeholders to trace the journey of coffee beans from cultivation to consumption. Initiatives such as Farmer Connect and IBM Food Trust have successfully implemented blockchain solutions, providing consumers with detailed insights into coffee origin and quality, thus fostering trust and fair-trade practices. Data analytics, another transformative force, has gained prominence within the coffee industry [137]. Stakeholders leverage advanced analytical tools to dissect extensive datasets encompassing aspects of production, quality, and consumer preferences [138]. This data-driven approach facilitates informed decision-making, process optimization and enhancement avenues [139]. For instance, coffee farmers utilize data on weather patterns, soil conditions, and farming techniques to make informed decisions, ultimately elevating yield, quality, and sustainability practices [140,141]. The rise of the Internet of Things (IoT) has introduced novel monitoring and optimization prospects [142], with strategically deployed IoT devices monitoring critical factors such as temperature, humidity, and storage conditions at various stages in real-time [143–146]. These devices contribute to risk identification, quality control, and waste minimization, exemplified by the use of

Table 11
Innovation and technology integration in the coffee supply chain processes and sustainability standards aligned with Sustainable Development Goals (SDGs).

Process	Older methods	Innovation and technology	Sustainability standards according to technology justified	SDGs
Harvesting	Handpicking	Mechanical harvesters, IoT sensors, robotics	Reduced labor costs, increased efficiency	1, 8
Processing	Wet processing	Eco-friendly dry processing techniques, Blockchain traceability, AI sorting	Reduced water usage, lower environmental impact	6, 12
Transportation	Manual transport	Automated logistics systems, GPS tracking, Autonomous vehicles	Lower carbon footprint, faster delivery	9, 13
Roasting	Traditional drum roasters	Precision roasting machines, AI control, data analytics	Energy efficiency, consistent quality	7, 12
Packaging	Manual bagging	Automated packaging lines, RFID tags, smart packaging, QR coding	Reduced packaging waste, improved hygiene	12, 14
Quality control	Visual inspection	AI-based quality monitoring systems, big data analytics, computer vision	Enhanced accuracy, reduced defects	9, 12

IoT-enabled sensors to monitor storage conditions during transportation, guaranteeing that coffee beans are stored within optimal temperature and humidity ranges to preserve desired quality. Furthermore, artificial intelligence (AI) and geographic information systems (GIS) play crucial roles in addressing key supply chain challenges in the coffee industry [139,147]. AI algorithms analyze vast datasets to optimize various aspects of the supply chain, from forecasting demand to improving logistics efficiency [148]. GIS technology facilitates spatial analysis and visualization, aiding in location-based decision-making and optimizing transportation routes [149,150]. Moreover, technology has facilitated opportunities for repurposing coffee waste, aligning with sustainability goals within the supply chain. Coffee waste finds utility in the production of biofuels, and renewable energy, and natural fertilizers [151–153] with innovative applications, such as biodegradable packaging materials [154,155] contributing to the circular economy. The integration of innovative technologies into the coffee supply chain considering Sustainable Development Goals (SDGs), as outlined in Table 11, not only enhances operational efficiency and reduces costs but also increases product transparency and traceability, thereby fostering more sustainable and ethical practices throughout the value chain.

While the potential of technology and innovation is immense, challenges including cost implications, infrastructure limitations, and resistance to change may impede widespread adoption. Nonetheless, as technology becomes more accessible, the coffee industry is poised to progressively integrate these advancements, promising heightened efficiency, sustainability, and circularity throughout the entire supply chain.

5. Discussion

Building on the thematic clusters derived from RQ1–RQ4, this section critically reflects on systemic challenges, sectoral trends, and actionable opportunities across the coffee supply chain. It provides a comparative perspective that highlights the distinct contributions of the present study in contrast to prior fragmented literature.

5.1. Climate vulnerabilities and sustainable practices

Climate change emerged as a key threat affecting coffee growers, as highlighted in RQ1 and RQ3. While previous research (e.g., [156–158]) has documented climate-related threats to coffee production, our study contributes a triangulated analysis that links these climatic stressors to both stakeholder adaptation (RQ1) and reuse innovation (RQ2). The results underscore how unpredictable rainfall, temperature shifts, and extreme events diminish crop yield reliability [21,58,159]. What sets our approach apart is its emphasis on multi-actor collaboration and how agroecological innovations such as shade-grown coffee and agroforestry systems [160–164] serve as climate buffers and enablers of circularity and biodiversity. Climate-resilient coffee varieties and sustainable certification programs further mitigate climate risks and promote ethical practices [165–167] are not discussed in isolation but framed as part of coordinated policy and practice recommendations. Collaboration among stakeholders and community-led adaptation programs provide essential support to coffee growers [168], reflecting the industry's commitment to addressing climate vulnerabilities and fostering sustainability [169–171]. These findings provide actionable strategies for climate resilience, which align with the reuse and innovation pathways explored under RQ2 and RQ4.

5.2. Global trade complexities

Exporters and importers, as discussed in RQ1, navigate complex trade networks influenced by market volatility, currency fluctuations, and shifting policy landscapes [172–174]. Currency fluctuations add to trade complexities, necessitating financial planning and risk management [175,176]. These dynamics emphasize the importance of financial planning and digital trade facilitation. Earlier literature has focused on documenting these challenges; however, our findings (via RQ1 and RQ4) extend the dialogue by evaluating the enabling role of digital trade tools and strategic alliances that offer stakeholders mechanisms to enhance operational efficiency and competitiveness [177–179]. This directly relates to the broader digital integration themes discussed in RQ4. We propose that digitization does not merely improve transactional efficiency but redefines competitive advantage within sustainable supply networks. This link between digital innovation and trade resilience remains underexplored in prior works, making our results a novel addition.

5.3. Quality maintenance and market dynamics for roasters and manufacturers

For roasters and manufacturers, balancing consistency and innovation emerged as a key theme under RQ1 and RQ3. Past studies [180,181] have acknowledged the sensory and process challenges in roasting, yet our research integrates these issues within the broader market adaptation context highlighted in RQ3. By emphasizing that maintaining flavor profiles [182] while adapting to dynamic consumer preferences [183,184] requires a careful blend of technological innovation and sensory science. Manufacturers increasingly face dual pressures of consistency and innovation. By aligning these pressures with technological advances and consumer behavior trends [185,186], this study offers a complete framing often absent in the literature. Recent innovations in roasting and sustainability practices [187,188] provide mechanisms to manage these tensions. The relevance of product differentiation, eco-friendly packaging, evolving consumer tastes, enhance competitiveness and direct trade partnerships [185,186,189] directly links with consumer-driven insights in RQ3.

5.4. Market competition and shifting consumer behaviors for retailers and cafés

Retailers and cafés are responding to increased market competition and changing consumer behaviors, as evidenced in RQ3, where technology-driven personalization and artisanal branding play a decisive role [190]. Unlike fragmented assessments seen in earlier works, our results (RQ3 and RQ4) provide a layered view of how traceability, mobile apps, and loyalty programs intersect with consumer psychology [191]. Technology adoption and collaboration with local roasters offer opportunities for customer engagement and authenticity [192,193]. Specialty cafés carve their niche by emphasizing artisanal craft and unique flavor profiles, resonating with consumers seeking distinct coffee experiences [194,195]. Retailers and cafés influence cultural aspects of coffee consumption and play a vital role in shaping consumer preferences to remain competitive and adapt to changing consumer behaviors [196] revealing alignment between innovation and sustainability trends. These insights extend the utility of prior findings by showcasing how cultural and digital shifts are jointly reshaping consumption ecosystems.

5.5. Sustainability and triple bottom line (Social, economic and environmental) implications

While multiple studies have explored individual sustainability dimensions [197], our integrative review consolidates these strands to demonstrate how reuse innovation (RQ2), stakeholder alignment (RQ1), and digital transparency (RQ4) together operationalize the triple bottom line. The study's findings affirm the growing emphasis on sustainability across social, environmental, and economic dimensions of the coffee value chain. As identified in RQ2 and RQ4, sustainable certifications and eco-friendly practices [198,199] improve ethical standards, while promoting community development, biodiversity conservation, and fair labor. Economic resilience is further supported through value addition,

Table 12
Social, economic, and environmental implications of implementing sustainable coffee practices and barriers to widespread adoption across the industry.

Category	Implications
Social	Community empowerment through access to information and resources
	Enhanced livelihoods for smallholder farmers through improved productivity
	Increased social inclusivity and gender equality in coffee farming communities
	Preservation of cultural heritage and traditional knowledge
Economic	Economic diversification and resilience in coffee-producing regions
	Creation of new job opportunities in the digital coffee value chain
	Improved market access and price transparency for small-scale coffee producers
	Strengthened local economies through value addition and processing
Environmental	Conservation of biodiversity and ecosystems through sustainable farming practices
	Reduction of carbon footprint through climate-smart agriculture
	Efficient water use and management to mitigate water scarcity
	Soil conservation and restoration to prevent erosion and degradation
	Adoption of agroforestry practices to promote ecological resilience

job creation, and traceable trade models, complemented by fair labor standards adopted by coffee companies [200]. Socially, our findings emphasize community empowerment through education and inclusivity [201]. Economically, we highlight diversification, price transparency, and improved traceability [202]. Environmentally, practices such as agroforestry, carbon reduction, and water conservation [203,204] reinforce ecological sustainability. This convergence of environmental, social, and economic value chains within a unified framework is rarely addressed holistically in existing literature, underlining the broader applicability of our findings. These broad sustainability implications are further detailed in Table 12, which summarizes the specific social, economic, and environmental benefits of implementing sustainable coffee practices, as well as highlighting key barriers to widespread adoption. Complementing this, Fig. 13 visually conceptualizes how the adoption of these sustainable practices can translate into tangible, future-positive impacts across the coffee supply chain

5.6. Research implications and future directions

The findings of this study provide a foundation for both academic and practical interventions in the coffee supply chain. For researchers, the framework encourages cross-disciplinary investigations that bridge environmental, social, and technological domains. Future studies should focus on longitudinal assessments of digital innovations and residue reuse impacts on supply chain resilience. For policymakers and industry stakeholders, the results highlight the urgency of fostering collaborative governance models that support smallholder empowerment, incentivize sustainable certifications, and invest in scalable digital traceability solutions Future policy should focus on facilitating these transitions to ensure a resilient and equitable coffee supply chain. Addressing infrastructural and financial barriers remains critical for widespread adoption of sustainable practices. Overall, sustained multi-sector engagement will be essential to realize the comprehensive sustainability transformation envisioned in this review.

6. Conclusion

This systematic review employs a combined qualitative and bibliometric approach to map the evolving landscape of sustainability within the global coffee supply chain. By analyzing 137 peer-reviewed articles spanning over two decades, it reveals critical interactions between stakeholder dynamics, residue valorization, consumer behavior, and digital technologies areas often examined in isolation. The study's hybrid approach offers new insights into how these dimensions collectively influence resilience, equity, and environmental stewardship in coffee production and trade. Key findings highlight how agroecological practices, circular economy principles, and technology-driven transparency combine to mitigate climate risks, enhance market efficiency, and promote socially inclusive growth. Initiatives promoting sustainable farming and equitable trade arrangements emerge as potential avenues for community empowerment and improved quality yields. However, challenges such as market volatility, currency fluctuations, and logistical complexities persist, stressing the need for adaptive strategies and strategic collaborations across stakeholders. Beyond combining existing knowledge, this work proposes a structured agenda for research and policy, emphasizing the importance of cross-sector collaboration. Future studies should prioritize longitudinal assessments to monitor evolving sustainability impacts and conduct regional comparative analyses to address contextual differences. Moreover, deeper investigations into the socio-economic effects of sustainable practices on local communities will be vital for shaping equitable development pathways. The study's hybrid methodology combining rigorous PRISMA-guided synthesis with advanced bibliometric mapping, demonstrates a replicable model for interdisciplinary sustainability research. It identifies critical knowledge gaps and underexplored intersections, supporting future inquiry into longitudinal trends, regional variations, and socio-economic outcomes. While comprehensive, this review acknowledges limitations including reliance on Scopus-indexed literature and language restrictions, which may exclude relevant research from other databases or linguistic domains. These factors highlight the need for ongoing adaptive inquiry to refine understanding as the coffee sector evolves. Ultimately, this study lays a robust foundation for advancing sustainability transformations in the coffee industry, contributing strategically to global goals for inclusive, resilient, and climate-smart food systems.

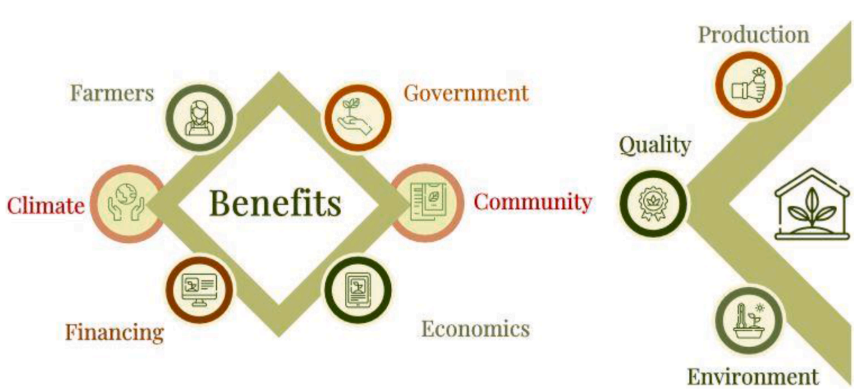

Fig. 13. Envisioning the future impact of sustainable practices.

CRediT authorship contribution statement

Fabio De Felice: Writing – original draft, Validation, Supervision, Data curation, Conceptualization. **Mizna Rehman:** Methodology, Data curation, Conceptualization. **Antonella Petrillo:** Writing – original draft, Validation, Data curation, Conceptualization. **Ilaria Baffo:** Writing – original draft, Validation, Supervision, Data curation, Conceptualization.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.101105.

Data availability

No data was used for the research described in the article.

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