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ORIGINAL PAPER

Circular Economy in Agrifood RD&I: A Global Bibliometric Review

Marcos Antonio Gomes Pena Jr.[2] · **Sérgio Saraiva Nazareno dos Anjos**[1] · **Fabrício Oliveira Leitão**[2]

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Abstract

This study examines how circular economy (CE) has been incorporated into the scientific domain of agrifood research, development, and innovation (RD&I), focusing on the conceptual structure, thematic evolution, and dominant innovation orientations that characterize this interface. Although CE has become increasingly prominent in sustainability debates, its integration into agrifood RD&I remains fragmented and uneven, particularly regarding the articulation between circularity principles, technological innovation, and regenerative systemic transformation. To address this gap, a structured bibliometric analysis was conducted using data retrieved from the Web of Science Core Collection, Scopus, CAB Abstracts, Dimensions, and FAO AGRIS databases. The final corpus comprised 1,456 journal articles published between 2023 and March 2026. Performance analysis and science mapping techniques were applied through the Bibliometrix package in R to examine keyword co-occurrence, thematic evolution, conceptual clustering, and collaboration patterns. The results show that the field is expanding rapidly but without a corresponding stabilization of its conceptual core. Circular economy operates as a broad integrative framework linking sustainability, waste management, biomass valorization, and life cycle assessment, while emerging technologies such as artificial intelligence and blockchain remain structurally secondary. This indicates that, despite their growing prominence in policy and strategic discourse, digital agriculture-related technologies have not yet become a central research front in circular economy-oriented agrifood RD&I, remaining substantially peripheral to the dominant scientific structure of the field. Biomass-related pathways and efficiency-oriented approaches dominate the current architecture of the literature, whereas broader regenerative and system-level transition perspectives remain comparatively underdeveloped. The findings indicate that CE has been incorporated into agrifood RD&I through a hybrid and asymmetric process in which sustainability framing, resource recovery, and technology-oriented innovation coexist without full conceptual integration. These results provide an empirical basis for advancing more coherent circular and regenerative agrifood RD&I agendas and for strengthening the integration between technological innovation, system-level transformation, and circularity principles.

Extended author information available on the last page of the article

Keywords Circular economy · Agrifood RD&I · Biomass valorization · Waste management · Bibliometric analysis

Introduction

Circular economy (CE) has become a major reference point in debates on sustainability transitions, resource efficiency, and new production models. While its principles have been widely discussed in industrial and urban systems, their incorporation into agriculture and agrifood systems remains more fragmented, especially when examined through the lens of research, development, and innovation (RD&I) [1, 2]. In the agricultural domain, this agenda is often expressed through the notion of *circular agriculture*, which seeks to reconnect production, regeneration, waste reuse, and resource efficiency within agroecosystems and value chains [3–5].

Despite promising isolated initiatives, the lack of a unified conceptual model limits CE's systematic integration into RD&I strategic planning and implementation of agricultural research initiatives [2]. Circular agriculture offers sustainable solutions for agricultural production; however, its effectiveness depends on the integration of CE concepts into the strategic agendas of RD&I institutions [6, 7]. This distinction is not trivial. In agrifood systems, CE cannot be reduced to the isolated adoption of cleaner techniques or waste-treatment solutions. Its stronger formulations imply a more systemic transition, involving the redesign of material and energy flows, the integration of environmental performance metrics, the reconfiguration of supply chains, and the alignment of innovation agendas with regenerative and efficiency-oriented practices [2, 6, 7].

As the final output of RD&I processes, technological innovation [8, 9] has historically played a decisive role in modernizing agriculture, increasing productivity, and enhancing competitiveness, particularly where public agricultural research systems have systematically shaped technological change as a development strategy [10, 11]. In this sense, the intersection between CE and agricultural RD&I is especially relevant. It concentrates a key tension of contemporary agrifood transitions: whether innovation remains primarily oriented toward efficiency within a prevailing linear logic, or whether it is increasingly associated with more circular and regenerative configurations of production [12].

Although digital agriculture, artificial intelligence, blockchain, and Agriculture 4.0/5.0 have increasingly been presented as strategic enablers of sustainability transitions, it remains unclear whether these technologies have effectively become central components of the scientific structure of circular economy-oriented agrifood RD&I or whether their prominence still reflects predominantly conceptual and policy expectations. Clarifying this distinction constitutes one of the analytical motivations of the present study.

Previous studies have shown that circular agriculture may offer pathways for reducing waste, improving input efficiency, strengthening ecosystem services, and connecting productivity goals with environmental regeneration [3–7]. At the same time, the strategic incorporation of these principles into agricultural RD&I agendas is still uneven [13, 14]. In different national settings, agricultural innovation has been shaped by policy, organizational change, and investment dynamics that historically prioritized productivity and competitiveness, with sustainability concerns often entering later or in a more fragmented way [10, 11].

Recent contributions reinforced that the operationalization of circular economy principles in production systems tends to materialize through the redesign of material flows and the reintegration of waste streams into production cycles [15]. Empirical evidence from manufacturing contexts shows that the incorporation of recycling and refurbishing processes into supply chains can significantly reduce waste generation (reaching reductions of up to 95% in specific industrial settings), while simultaneously lowering production costs and stabilizing operations under inflationary pressures [15].

Despite the growing recognition of CE in urban and industrial contexts, the lack of an integrated conceptual model that articulates CE principles with agrifood RD&I practices reveals a critical knowledge gap, particularly regarding the systematization of CE-oriented approaches for the sector [16].

In recent years, there has been a fast expansion of review-based research on circular economy (CE) in agriculture and agrifood systems, as will be discussed in the following sections. The scientific publications analyzed on this paper seek to organize the field and identify its main themes, methods, and implementation challenges. Their contributions tend to develop along specific analytical tracks, each of which captures only part of the broader relationship between CE and agrifood transformation driven by RD&I.

Agnusdei and Coluccia [17] conducted a bibliometric, network, and content analysis of sustainable agrifood supply chains and identified research clusters related to traceability, food security, resilience, and technological innovation, highlighting blockchain and post-consumption gaps as relevant future directions. More recently, Dieguez-Santana et al. [18] specifically examined the application of CE in the agrifood supply chain through a combined bibliometric, network, and content analysis, emphasizing emerging topics, barriers, and decision-making issues in circular supply chain management. Although these studies are highly relevant, their analytical center of gravity remains the supply chain and operational management domain, rather than the broader scientific structuring of CE within agrifood research and innovation systems. The present study addresses this latter perspective by investigating how CE has been incorporated into the scientific structure of agrifood research, development, and innovation (RD&I), rather than examining the operational implementation of CE in agrifood supply chains and their management, which constitutes the central focus of those previous studies.

This supply chain-oriented perspective is further supported by recent modeling approach that explicitly integrates circular economy principles into logistics and production systems, what is shown in Tyagi, Goel and Chauhan [19], details following. Optimization-based models have demonstrated how circular supply chains can be structured to simultaneously minimize costs, reduce environmental impacts, and improve system resilience through the reintegration of waste streams and the coordination of multiple actors. This represents an important contribution to the field by demonstrating how circular economy principles can be operationalized through supply chain optimization models. However, whereas that study focuses on the operational design and optimization of circular supply chains, the present study investigates how circular economy has been incorporated into the broader scientific structure of agrifood research, development, and innovation (RD&I). In industrial applications, such models incorporate key elements such as recycling flows, imperfect production processes, and inspection mechanisms to ensure quality and efficiency within circular loops, while also accounting for macroeconomic variables such as inflation and carbon emission constraints [19].

Scandurra et al. [20], for instance, examined the maturity level of the agrifood sector in the CE domain by analyzing inter- and intra-company circular practices and classifying them according to their degree of innovativeness. Their findings are important because they show that much of the circularity observed in the agrifood sector still has a predominantly conventional or incremental character. Similarly, Christ et al. [21] reviewed CE in the agrifood sector through a mixed-method design combining bibliometric mapping and qualitative content analysis, with a particular emphasis on interventions, outcomes, and the 9Rs framework. This contribution significantly improves the operational understanding of CE practices and their impacts across the agrifood sector. Nevertheless, both studies remain primarily oriented toward implementation patterns, practices, and intervention logics. These studies make important contributions to understanding the implementation of circular economy practices, intervention logics, and their impacts across the agrifood sector. However, their analytical focus remains on the implementation and operationalization of circular practices, whereas the present study investigates how circular economy has been incorporated into the broader scientific structure of agrifood research, development, and innovation (RD&I).

In parallel, some reviews have developed more sector-specific analytical lenses. Katiyar and Gedam [22] examined the circular economy in the fertilizer industry through a systematic and bibliometric review centered on Life Cycle Assessment (LCA) and the CE-LCA interface. Their study makes an important contribution by clarifying the limitations of conventional LCA for capturing circularity in fertilizer systems and by proposing a more integrated CE-LCA perspective. However, precisely because of its analytical design, this review is focused on a specific industrial-technological segment, rather than on the broader structuring of circularity across agrifood research fronts. However, precisely because of its analytical design, this review focuses on a specific industrial-technological segment and on the CE-LCA interface within fertilizer systems, whereas the present study investigates how circular economy has been incorporated into the broader scientific structure of agrifood research, development, and innovation (RD&I).

Taken together, these studies show that the literature on CE in agriculture and agrifood systems has advanced significantly. Existing reviews have already contributed to understanding supply chain circularity, implementation barriers, circular practices, sectoral maturity, waste valorization, and measurement approaches. However, as observed in the comparative examination of this literature (selected by an additional targeted screening within this study's own search string, expanded across all searchable fields with the terms "bibliometric*" and "systematic literature review" OR "systematic review", and included "reviews" among the filters), we did not identify studies that explicitly analyze how CE has been integrated into the scientific production related to agrifood research, development, and innovation (RD&I) as such.

This distinction is important. While prior reviews have made substantial contributions to scientific literature, they have generally organized the field around practices, supply chains, interventions, or sector-specific applications. They have not systematically examined the field from the perspective of agrifood RD&I as a knowledge-producing and innovation-orienting domain, that is, as the arena in which technological trajectories, conceptual priorities, and research agendas are formed and stabilized through scientific production.

The present study differs from previous reviews in at least three key dimensions. First, rather than focusing on a specific segment of the agrifood system (e.g., supply chains, fertilizer systems, or case-based circular practices), it investigates the broader scientific field at the intersection of CE, agriculture/agrifood, and technological innovation, thereby capturing how circularity has been articulated within agrifood RD&I-related literature. Second, the study is not restricted to cataloguing practices or interventions, but seeks to identify the conceptual structure, thematic evolution, and dominant orientations of innovation that have shaped the incorporation of CE into this field. Third, by interpreting the bibliometric evidence through the lens of RD&I, the article moves beyond a conventional descriptive mapping exercise and contributes to clarifying whether the literature has been organized primarily around efficiency-oriented technical solutions or whether it also indicates movement toward broader circular and regenerative innovation configurations.

Thus, this study aims to systematize the available scientific knowledge on CE in agrifood RD&I, assess the current lack of research integration at this interface, and identify the main thematic structures, innovation orientations, and gaps that may guide future studies in the area (this is the step 1 on the Fig. 2).

This study examines how the scientific literature itself has organized, prioritized, and framed the CE agenda in agrifood RD&I. More specifically, it asks three questions: (i) How is the global agrifood RD&I conceptually structured on CE? (ii) How has this field evolved thematically between 2023 and 2026? and (iii) To what extent does the literature indicate movement from process-specific circularity solutions toward broader system-level agrifood RD&I CE transition concerns? By addressing these questions, the article shifts the focus from merely identifying CE practices in agrifood sector to uncover potential movements towards agrifood RD&I CE transition, which is its objective.

The main research gap addressed in this study lies in the limited understanding of how CE has been integrated into the scientific domain of agrifood RD&I, and of which orientations of innovation have dominated this integration [3, 6, 20, 23]. Accordingly, the present bibliometric analysis is designed to investigate how CE has been incorporated into agrifood RD&I-related scientific production, with particular attention to its conceptual structure, thematic evolution, and dominant orientations within the scientific and organizational literature.

This study contributes by mapping the conceptual structure of the field, identifying its main thematic trajectories, and revealing asymmetries in the way circularity has been articulated in agrifood RD&I. In this sense, the study is guided by a preliminary model of "circular convergence in agrifood research", understood here as the partial and uneven convergence among three dimensions visible in the literature: (i) CE as normative-conceptual basis; (ii) regenerative technologies (e.g., anaerobic digestion, pyrolysis); and (iii) LCA-based systemic assessments. These dimensions intersect in the integration of emerging technologies and local agrifood chains in low-capacity settings.

Based on this perspective, this study conducts a bibliometric analysis of the global scientific literature on technologies and research developments in agrifood directed to move the sector towards CE. The findings are expected to contribute to three levels of discussion:

Economic: Identification of strategic areas and collaboration networks for guiding efficient RD&I investments.

Social: Exposure of regional and thematic gaps in scientific output, affecting stakeholder inclusion.

Environmental: Assessment of how well CE principles are reflected in the literature, offering direction for sustainable agricultural RD&I.

In doing so, this study aims to provide a more robust basis for future research and for the alignment of agrifood RD&I agendas with circularity principles in a global context.

Circular Economy and Technologies for the Transition to Circular Agriculture

The circular economy (CE) has increasingly been discussed as a strategic framework for rethinking production and consumption systems in response to resource depletion, environmental degradation, and the structural limits of linear economic models [6]. In agriculture and agrifood systems, this perspective has gained relevance because these sectors are simultaneously dependent on natural resources, highly exposed to environmental pressures, and strongly associated with waste generation, nutrient losses, and inefficiencies in material and energy use [6].

The Ellen MacArthur Foundation [24] advocates for a circular economy (CE) centered on regenerative processes, resource efficiency, and reduction of waste and pollution as a response to the degradation and depletion driven by linear economic models. In that report, the foundation outlined key principles, including the elimination of waste and pollution, keeping products and materials in use, and regenerating natural systems. These principles offer a systemic framework for sustainable development, emphasizing closed-loop systems and holistic resource management across different production stages, as illustrated in the "circular economy system diagram" (Fig. 1).

The transition from a linear economy based on extract-produce-dispose logic to CE represents a paradigm shift in contemporary economic and business thinking [25, 26]. CE

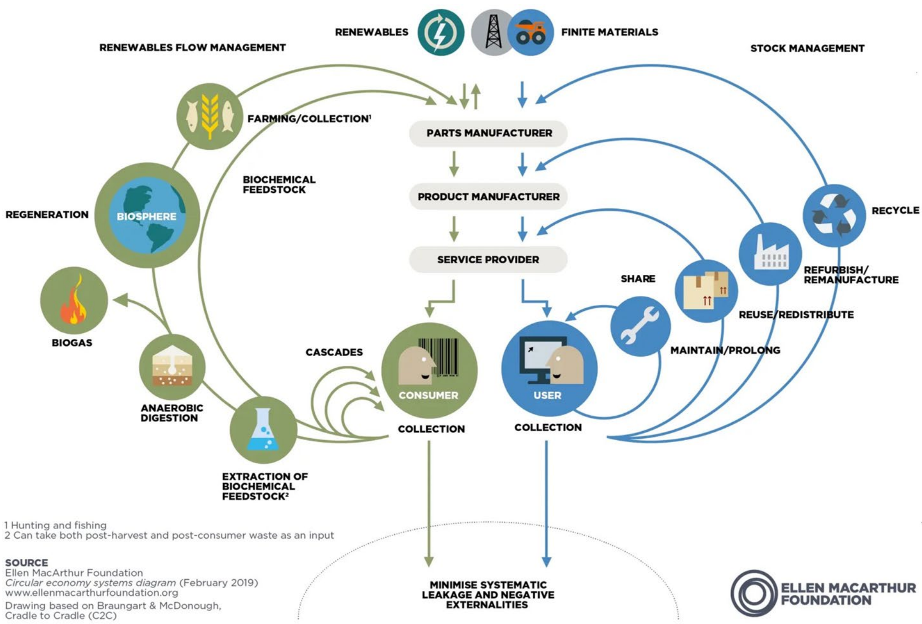

Fig. 1 Circular economy systems diagram (Butterfly Diagram). Source: Ellen MacArthur Foundation

promotes a regenerative model that aims to retain the value of products, materials, and resources in the economy for as long as possible while minimizing waste and environmental impact [25, 27]. This approach requires not only technological innovations, but also the reconfiguration of business models, supply chains, and production processes, with an emphasis on resource efficiency, eco-design, and a shift from ownership to use [28, 29].

According to Tukker [30], this transformation demands a new systemic understanding of production and consumption, whereas Geissdoerfer et al. [27] highlighted the integration of environmental sustainability, economic performance, and business innovation. Few studies address circular consumption and consumer behavior in agriculture [31]. This transition requires scrutiny of social and ethical assumptions, especially benefit distribution and feasibility across diverse contexts [32].

Reliance on a linear economy based on finite resources exacerbates environmental degradation [33]. The linear model perpetuates a “take-make-waste” approach, leading to waste accumulation and pollution [26].

The circular economy is grounded in the principles of reducing resource consumption, reusing materials and products, and recycling waste streams to minimize environmental externalities and maintain resource value within production systems for as long as possible. In contrast to the traditional linear “take-make-dispose” model, circular approaches seek to decouple economic activity from intensive resource depletion by promoting regenerative and restorative production dynamics, particularly within agrifood systems [26, 27].

In this sense, nowadays the circular economy is associated with sustainability because it contributes to resource efficiency, waste reduction, environmental resilience, and the transition toward more sustainable agricultural and food production systems [6, 16].

CE has often been associated with the reduction of waste, the reuse and valorization of by-products, the extension of resource utility, and the search for more regenerative and efficient production arrangements in food and agricultural systems [23, 34].

Dependence on finite resources also poses a risk to long-term economic stability [35–37]. Food systems rely heavily on fossil fuels and generate significant waste, reflecting the unsustainable linear model [26, 38]. Agriculture drives regional development by producing food, raw materials, and energy, while sustaining rural employment and territories [39]. Conventional agricultural practices operate under the linear “take-make-waste” paradigm, accelerating resource depletion and environmental degradation and highlighting the urgent need for more resilient and sustainable circular models [38–41].

The prevailing linear model in agriculture reduces efficiency and increases waste, economic loss, and environmental damage [40, 42]. Traditional farming practices often involve the excessive use of inputs such as water, fertilizers, and pesticides, which contribute to soil degradation, water pollution, and biodiversity loss [43]. Shifting to CE in agriculture enables waste valorization, cost reduction, and greater agro-industrial efficiency [39, 42]. Dey et al. [44] identify crop rotation, organic farming, and efficient water use as key CE practices in agriculture. These approaches lower emissions, reduce chemical inputs, and improve soil and biodiversity [38, 42]. Precision agriculture significantly reduces input use and waste [45, 46]. It also supports climate mitigation through resource optimization [47, 48]. Conservation and precision farming reduce nitrogen use while preserving productivity [49, 50]. Agroecology reinforces circularity by embedding ecological principles in agriculture [51].

CE integration in agriculture reflects Georgescu-Roegen's notions of scarcity and environmental degradation [52]. They enhance ecosystem services, reduce input dependency, and improve resilience to market and environmental shocks [53, 54]. Thus, the emerging concept of circular agriculture is grounded in CE principles. Circular agriculture aims to increase output while conserving resources, reducing degradation, and enhancing well-being [3, 55]. Velasco-Muñoz et al. [6] defined circular agriculture as a set of farming activities aimed at ensuring regeneration and biodiversity within agroecosystems and surrounding ecosystems based on the three pillars of agricultural sustainability (social, environmental, and economic) through the efficient and effective use of resources throughout the value chain [56].

A second strand of the literature is more directly associated with agrifood supply chains, where circularity is examined in relation to food loss and waste prevention, reverse logistics, traceability, and circular business model adaptation across food-system operations [23, 37]. A third strand increasingly connects CE to circular bioeconomy transitions, especially through the valorization of agricultural residues, biomass reuse, and the repositioning of agricultural outputs as feedstocks for bio-based production systems [34].

Recent review-based evidence suggests that these strands have often been developed through specific thematic or operational lenses [6, 23, 34]. This is particularly relevant because part of the literature has shown that many circular practices identified in the agrifood sector are still concentrated in conventional or incremental approaches, with a stronger emphasis on recovery and reduction strategies than on radically innovative transformations [20].

Taken together, these strands suggest that the recent CE literature in agrifood has become broader and more diversified, but they also indicate that the field is still marked by heterogeneous analytical emphases, especially regarding how circularity is linked to innovation, transformation, and system reconfiguration in agriculture [3, 6, 20, 34]. Similarly, studies on circular agriculture have argued that circular initiatives may differ substantially in their transformative potential, indicating that not every circular practice necessarily corresponds to deeper systemic change in food and agricultural systems [3].

Velasco-Muñoz et al. [6], Zhang et al. [23] and Khanna et al. [34] point that some studies have made important contributions to the understanding of CE in agriculture and agrifood by mapping topics such as lifecycle applications, circular agricultural practices, food-system circularity, supply-chain issues, and bioeconomy-related valorization pathways. However, these studies do not yet provide a sufficiently clear picture of how CE principles have been incorporated into agrifood RD&I-related scientific production itself. This is particularly marked when RD&I is understood as the domain in which research agendas, technological orientations, and innovation priorities are expressed through scientific output [6, 23].

More specifically, the existing literature still doesn't clearly indicate which technological and thematic domains have most strongly mediated the incorporation of CE into agrifood innovation-oriented research. Besides, this incorporation hasn't occurred mainly through operational and efficiency-oriented approaches or through broader transition-oriented circular and regenerative perspectives [3, 20, 57].

This distinction is analytically relevant because recent studies on circular agriculture and agrifood transitions have emphasized that the move toward circular models may involve different degrees of transformation (ranging from incremental adaptations to more systemic reconfigurations of production and supply systems) [3, 57].

This gap is relevant because the presence of CE-related practices alone does not necessarily indicate a deeper reorientation of agrifood innovation systems. Scientific production also reveals how research agendas are organized, which technologies are prioritized, and how circularity is being framed within the field. In this sense, the unresolved issue is not simply whether CE is present in agrifood research, but how it has been structured within the knowledge base that informs agricultural RD&I.

It is this gap that the present bibliometric analysis seeks to address by examining the conceptual structure, thematic evolution, and dominant orientations of the literature at the intersection of CE, agriculture/agrifood systems, and technology incorporated into them.

Methods and Procedures

Bibliometrics is a semi-quantitative method for extracting evidence from scientific and institutional publications to inform or forecast phenomena [58]. They offer strategic insights by mapping the state of the art, identifying research gaps, contextualizing contributions, and guiding RD&I evaluation [58–60].

This study adopts a structured bibliometric approach to examine how circular economy (CE) has been incorporated into agrifood research, development, and innovation (RD&I)-related scientific production. Bibliometric analysis is employed as a systematic method for mapping scientific fields, identifying conceptual structures, and analyzing the evolution of research agendas based on large-scale bibliographic data.

The methodological design follows established bibliometric research protocols, particularly the guidelines proposed by Donthu et al. [60], the analytical framework of Zupic and Čater [61], and the science mapping workflow operationalized through the Bibliometrix package described by Aria and Cuccurullo [62]. In line with these references, the study integrates performance analysis and science mapping to examine both the structural dynamics and the conceptual organization of the field.

The analytical design of this study combines two complementary dimensions of bibliometric inquiry. First, performance analysis is used to characterize the development of the field through indicators of scientific production, citation patterns, and source relevance. Second, science mapping is employed to identify the conceptual and relational structure of the literature, including thematic configurations, keyword associations, and intellectual clustering.

Following Zupic and Čater [61], this combination allows the analysis to move beyond descriptive statistics and toward the identification of knowledge structures and research trajectories. In this study, this distinction is central, as the objective is to examine how the field has been organized in terms of innovation orientation, thematic consolidation, and conceptual articulation.

To achieve the objective, this bibliometric study maps research at the intersection of circular economy, technology, and agriculture (see Fig. 2). The dataset was constructed through a comprehensive search strategy designed to capture scientific production at the intersection of three analytical domains:

(i) circular economy;
(ii) agriculture and agrifood systems; and.

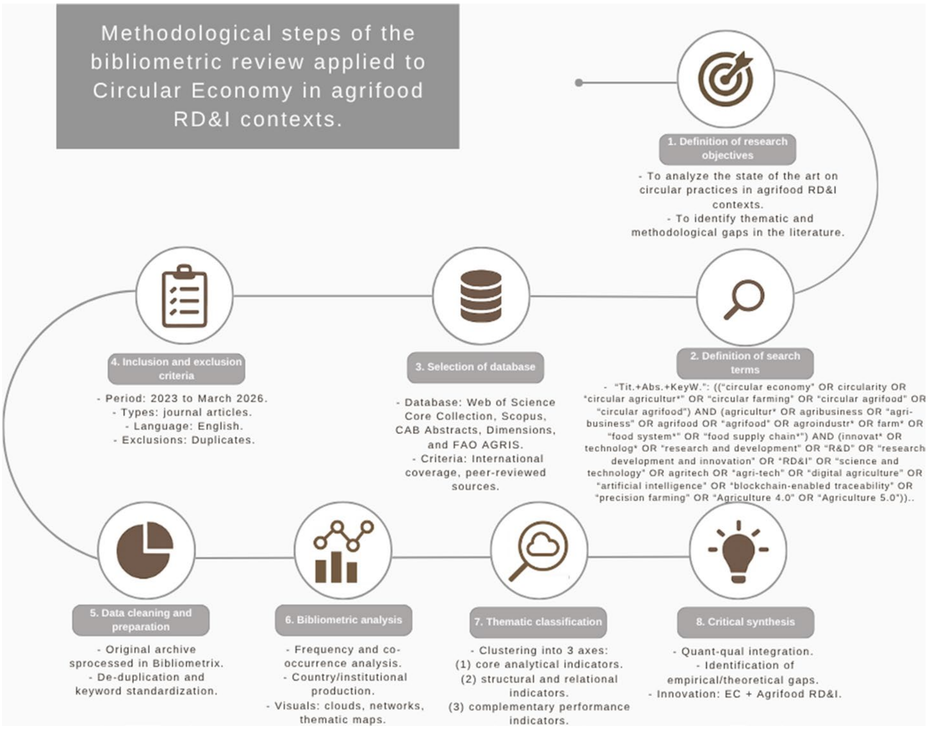

Fig. 2 Steps of the bibliometric analysis applied to the circular economy in the context of agrifood RD&I. Source: Authors, based on [60–62]

(iii) innovation and technology-related research.

a. Definition of the research scope and database:

To ensure conceptual breadth and terminological coverage, the search string incorporated multiple descriptors and synonyms within each domain, combined through Boolean operators. The final search expression was defined as (this is the step 2 on Fig. 2):

(("circular economy" OR circularity OR "circular agricultur*" OR "circular farming" OR "circular agrifood") AND (agricultur* OR agribusiness OR "agri-business" OR agrifood OR "agrifood" OR agroindustr* OR farm* OR "food system*" OR "food supply chain*") AND (innovat* OR technolog* OR "research and development" OR "R&D" OR "research development and innovation" OR "RD&I" OR "science and technology" OR agritech OR "agri-tech" OR "digital agriculture" OR "artificial intelligence" OR "blockchain-enabled traceability" OR "precision farming" OR "Agriculture 4.0" OR "Agriculture 5.0")).

The search was conducted in multiple international bibliographic databases (this is the step 3 on Fig. 2): Web of Science Core Collection, Scopus, CAB Abstracts, Dimensions, and FAO AGRIS. The search expression was applied to fields equivalent to title, abstract, and keywords, according to the indexing structure of each platform. The search was conducted on March 30 2026 (Scopus, CAB Abstracts, Dimensions and FAO AGRIS), and March 31 2026(Web of Science Core Collection).

The use of multiple databases aimed to ensure adequate coverage of the scientific literature and to account for differences in indexing scope across platforms. Those procedures are consistent with bibliometric best practices for ensuring broad yet structured retrieval [60].

b. Inclusion criteria and temporal delimitation (this is the step 4 on Fig. 2):

To ensure analytical focus and comparability over time, the dataset was refined to include only the documents published between 2023 and 2026 (inclusive). This temporal window was selected to capture recent trends and emerging themes in CE, as applied to the agricultural sector, following the approach of Strozzi et al. [63] in smart factories. We additionally filtered the results by journal articles and only in English language.

In summary, the inclusion criteria applied were:

- document type: journal articles (only);
- language: English;
- timeframe: publications from 2023 to March 2026.

This temporal delimitation reflects the study's focus on the current configuration of the scientific agenda, rather than its historical development.

Furthermore, a complementary identification of previous bibliometric and systematic review studies within the same conceptual domain was carried out, using the same search string with the addition of the descriptors "bibliometric*" and " "systematic review" OR "systematic literature review" ". This step allowed for a comparative positioning of the study in the literature, without altering the composition of the analytical dataset.

c. Data retrieval and organization:

The initial search returned:

- Web of Science Core Collection: 1,043 results;
- Scopus: 1,101 results;
- CAB Abstracts: 5 results;
- Dimensions: 98 results;
- FAO AGRIS: 0 results.

All metadata were exported and saved in ".txt" and ".csv" formats, and organized as the approach consistent with procedures described by Rejeb et al. [64].

d. Data processing and analytical environment (this is the step 5 on Fig. 2):

All records were exported in formats preserving full bibliographic metadata and cited references. No articles were excluded from the final dataset based on textual screening procedures (e.g., title and abstract screening). The analysis was conducted exclusively using the Bibliometrix package and its Biblioshiny interface in R, which provides an integrated environment for performance analysis and science mapping, following the steps of Aria and Cuccurullo [62, 65].

The use of Bibliometrix ensures methodological transparency and reproducibility, as it allows the execution of standardized workflows for data cleaning, indicator calculation, and thematic analysis within a unified computational framework.

The files of each database were imported into the Bibliometrix package in R, and were combined, eliminating the duplicates (use of these tools follows consolidated practices in the recent literature [63]).

This methodological design ensures the reproducibility of the bibliometric procedure and reliability of the resulting indicators [64, 65]. Moreover, it aligns with the international best practices recommended by Gautam, Kodama, and Enomoto [66] for constructing science maps and analyzing scientific collaboration networks, even in interdisciplinary contexts. (Fig. 3).

The steps are detailed in Fig. 2 (a structured bibliometric protocol [65]).

e. Bibliometric indicators and analytical procedures (this is the rationale to steps 6–8 on Fig. 2):

The selection and organization of bibliometric indicators followed a purpose-driven analytical logic, in line with established bibliometric guidelines [60]. The indicators were structured hierarchically according to their contribution to the central objective of the study: to understand how circular economy (CE) has been conceptually structured, thematically developed, and progressively incorporated into agrifood RD&I-related scientific production.

Accordingly, the analytical framework is organized into three interconnected levels:

(i) core analytical indicators, which directly support the interpretation of conceptual structure and thematic evolution;

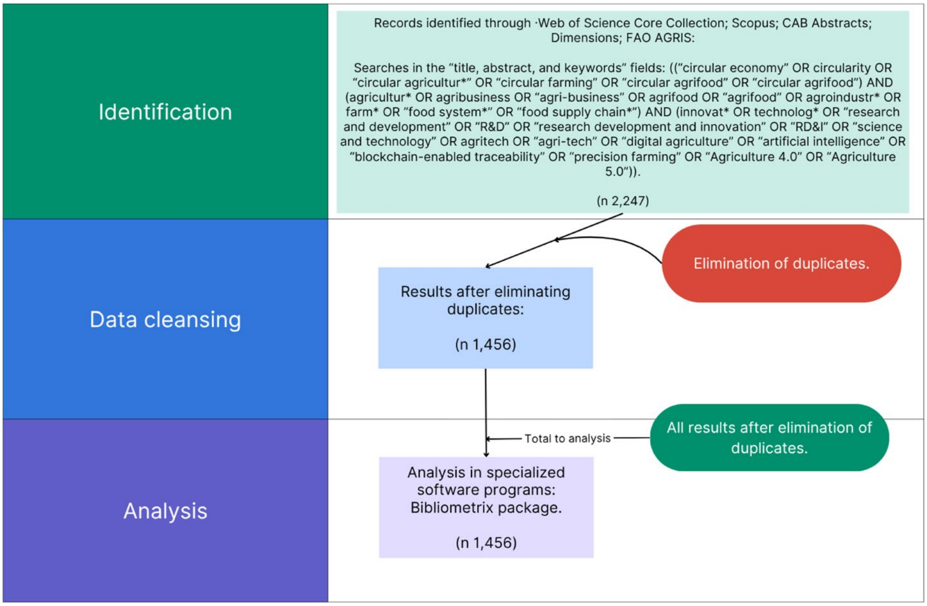

Fig. 3 Phases of the research execution. Source: Authors, based on [65]

(ii) structural and relational indicators, which contextualize the organization of the scientific field; and.
(iii) complementary performance indicators, which provide descriptive support for the overall characterization of the literature.

i) Core analytical indicators

This first group constitutes the central analytical axis of the study, as it directly addresses how CE is articulated within agrifood RD&I-related research. The analysis employs:

- keyword frequency analysis, to identify the most recurrent concepts and terminologies associated with CE in RD&I in agrifood systems;
- keyword co-occurrence networks, to reveal patterns of conceptual association and to identify clusters of interrelated research themes;
- factorial analysis of keyword clusters, to uncover the latent conceptual structure of the field and to distinguish major thematic groupings;
- thematic mapping, to classify themes according to their relevance and development, distinguishing between motor themes, basic themes, emerging or declining themes, and niche themes;
- thematic evolution analysis, to track how research themes have developed and shifted over time;
- trend topic analysis, to identify the temporal dynamics of specific research topics and detect emerging directions;
- word dynamics, to capture changes in the relative importance of key concepts across the analyzed period.

Together, these indicators allow the reconstruction of the conceptual architecture of the field, making it possible to assess:

- which themes constitute the core of CE-related agrifood RD&I research;
- how these themes are interconnected;
- how the research agenda has evolved over time; and.
- whether the incorporation of CE is associated with efficiency-oriented approaches or with broader circular and regenerative innovation trajectories.

ii) Structural and relational indicators

The second group of indicators provides the structural context within which the conceptual developments identified above take place. These indicators allow the analysis of how scientific production is organized across authors, institutions, countries, and collaboration networks. The analysis includes:

- co-authorship networks, to examine patterns of collaboration among researchers;
- country-level collaboration networks and production, to identify geographic concentration and international linkages;
- corresponding-author distributions, to assess leadership patterns in scientific production;

- affiliation-level production over time, to identify institutional dynamics;
- source-level production over time, to examine how publication outlets contribute to the evolution of the field.

These indicators contribute to understanding how the scientific field is structured in terms of collaborative networks and institutional distribution, providing insight into the environments in which CE-related agrifood RD&I research is produced and disseminated.

iii) Complementary performance indicators

The third group includes indicators that characterize the productivity and impact structure of the literature, providing a descriptive foundation that supports the interpretation of the core analytical results. The analysis shows:

- annual scientific production and annual citation dynamics, to assess the expansion and consolidation of the field;
- most relevant authors and sources, to identify key contributors;
- most globally cited documents, to capture highly influential publications;
- most cited countries, to assess geographic influence;
- author- and source-level indices (h-index, g-index, m-index), to capture complementary dimensions of productivity and citation impact.

These indicators are not interpreted as standalone measures of scientific quality, but as complementary descriptors that help contextualize the distribution of influence and productivity within the field.

The three groups of indicators are not treated independently but are analytically integrated. While performance and structural indicators provide the empirical context of the field, the core analytical indicators guide the interpretation of how CE has been incorporated into agrifood RD&I-related literature.

This hierarchical organization ensures that the study moves beyond conventional descriptive bibliometric approaches and instead focuses on identifying the conceptual structure of the field, the evolution of research themes and the dominant orientations of scientific production (particularly in relation to the role of circular economy in shaping agrifood innovation).

Results and Discussion

The corpus comprises 1,456 documents, produced by 6,548 authors, across 656 journals, with an average of five co-authors per paper. These data situate the field within a highly collaborative and distributed mode of knowledge production.

The number of publications increases sharply from 231 (2023) to 659 (2025). At the same time, average citations per article fall from 21.22 to 3.27 over the same period. Taken in isolation, this decline might suggest a weakening of impact. Read together, however, this demonstrates that the field is expanding faster than it can accumulate recognition. In bibliometric terms, this is a hallmark of agenda acceleration. The research at the intersection of circular economy (CE), agrifood systems, and innovation has moved into a phase of rapid expansion. (Table 1).

Table 1 Data main information

Description	Results
Sources (Journals)	656
Documents	1,456
Average citations per doc	7.566
Keywords plus (ID)	4,566
Author's keywords (DE)	4,451
Authors	6,548
Authors of single-authored docs	71
Co-authors per doc	5.03
International co-authorships %	0.8242

Source: Authors, with data generated in Bibliometrix

One major point that emerges from the dataset is that research on CE in agrifood systems has expanded faster than its intellectual structure has stabilized. This distinction matters. In a consolidated field, publication growth is usually accompanied by a clearer hierarchy of references, tighter clustering around established research fronts, and stronger convergence between productivity and influence. That is not what the present data show.

A second layer of evidence reinforces this interpretation. The expansion isn't driven by a narrow set of actors or outlets. Production over time (whether observed at the level of authors, sources, or affiliations) shows a broadening base. In other words, the field is not consolidating around a stable group of contributors, but it is opening outward.

This observation is analytically significant because it suggests that circular economy has not yet become conceptually consolidated as a stable organizing framework within agrifood RD&I. Instead, it continues to be explored through multiple thematic and disciplinary entry points. This interpretation is consistent with the evolution of emerging scientific domains, in which rapid publication growth commonly precedes conceptual stabilization and the formation of a more cohesive cognitive structure [60, 61, 67]. Consequently, the observed growth should be interpreted less as evidence of a consolidated field than as the expansion of an increasingly populated research domain whose internal organization remains under construction.

Once the field is viewed through the lens of influence rather than volume, its internal structure becomes less intuitive. Once output is crossed with the adjusted author indices, the picture becomes more interesting. This divergence between productivity and influence suggests that the field is still in a stage where select contributions define trajectories.

The strongest positions in Table 2 are more differentiated. The combined presentation of the h-index, total citations, number of published papers, and fractionalized articles provides a more comprehensive assessment of authors' scientific performance by jointly capturing productivity, scholarly impact, and individual contribution to collaborative research [60, 65]. Sharma, M. and Shon, H. K. each reach h-index = 6, with 150 and 156 total citations, respectively. Kumar, V. also reaches h-index = 6, but with 78 citations, suggesting a different influence profile. By contrast, Kumar, A. has only 6 published papers, yet accumulates 229 citations, far above several more prolific authors. Li, Y., despite leading in output, records 35 total citations, which places him in a different position within the field's influence structure.

This shows that the field is shaped by a smaller number of contributions that have acquired disproportionate interpretive or methodological weight. In a young and fast-expanding field, this kind of asymmetry is common. Some authors become central because they produce

Table 2 Authors' perfomances

Author	h-index	Total citations	Number of published papers	Articles fractionalized
Kumar, V.	6	78	6	0.76
Sharma, M.	6	150	8	1.07
Shon, H. K.	6	156	8	1.80
Joshi, S.	5	130	5	0.94
Li, Y.	5	35	11	2.12
Zhang, Y.	5	38	11	1.18
Kumar, A.	4	229	6	1.43
Kumar, P.	4	149	5	0.69
Liu, Y.	4	79	5	0.72
Naruetharadhol, P.	4	48	4	0.89
Sehnem, S.	4	31	5	1.67
Sridhar, K.	4	44	4	0.38
Adeniyi, A. G.	3	44	4	0.55
Ali, A.	3	42	3	0.95
Bag, S.	3	43	3	0.73
Bains, A.	3	37	3	0.25
Chawla, P.	3	24	3	0.38
Chen, C.	3	30	5	1.10
Emenike, E. C.	3	44	4	0.55
Gupta, V. K.	3	140	3	0.35
Huang, W.	3	30	5	0.95
Iwuozor, K. O.	3	44	4	0.55
Kazancoglu, Y.	3	128	3	0.62
Khan, M.	3	22	3	0.67
Kumar, R.	3	124	3	0.49

Source: Authors, with data generated in Bibliometrix

frameworks or references that travel more effectively across subtopics, while others contribute to expansion without exerting equivalent structuring force.

The same logic appears at the journal level (see Table 3). The presentation of the number of articles, h-index, g-index, m-index, and total citations combined provides a multidimensional assessment of journals by integrating complementary measures of publication productivity, citation impact, recognition of highly cited publications, and the temporal consistency of scientific influence, thereby offering a more robust evaluation than any single bibliometric indicator alone [60, 65, 68, 69]. *Sustainability* is by far the most prolific source, with 83 articles, followed by the *Journal of Cleaner Production* (39), the *Journal of Environmental Management* (25), and the *Science of the Total Environment* (20). But productivity again diverges from influence. The *Journal of Cleaner Production* records h-index = 17, g-index = 25, m-index = 4.25, and 662 total citations, slightly exceeding *Sustainability*, which has 646 citations despite more than double the number of articles. The *Science of the Total Environment* reaches 535 citations with only 20 papers, while *Sustainable Production and Consumption* reaches 296 citations from 14 articles.

This reveals a division of labor inside the field. Some journals (above all *Sustainability*) operate as major vehicles of thematic diffusion. Others (especially *Journal of Cleaner Pro-*

Table 3 Sources' performances

Sources	Articles	h_index	g_index	m_index	TC
Sustainability	83	12	23	3.00	646
Journal of Cleaner Production	39	17	25	4.25	662
Journal of Environmental Management	25	9	17	2.25	308
Science of the Total Environment	20	13	20	3.25	535
Frontiers in Sustainable Food Systems	17	7	10	1.75	115
Biomass & Bioenergy	17	7	9	3.50	85
Applied Sciences-Basel	17	5	8	1.25	71
Waste Management	15	7	14	1.75	198
Industrial Crops and Products	15	5	10	1.25	106
Sustainable Production and Consumption	14	7	14	1.75	296
Business Strategy and the Environment	14	4	9	1.00	83
Foods	13	7	10	1.75	118
Sustainable Futures	12	4	6	1.00	39
Journal of Water Process Engineering	11	7	11	1.75	165
Trends in Food Science & Technology	11	7	11	1.75	133
Environmental Science and Pollution Research	11	6	8	1.50	83
Journal of Environmental Chemical Engineering	11	5	6	1.25	41
Energies	11	4	5	1.00	31
Circular Economy and Sustainability	11	3	4	0.75	26
Discover Sustainability	11	2	6	0.67	44
Bioresource Technology	10	6	10	1.50	100
Agriculture-Basel	10	4	5	1.00	29
Sustainability (Switzerland)	10	3	6	0.75	38
Waste and Biomass Valorization	10	3	4	0.75	24
Biomass Conversion and Biorefinery	9	4	6	1.33	41
Agronomy-Basel	8	5	8	1.25	89
Chemosphere	6	6	6	1.50	399
Desalination	6	6	6	1.50	152
Bioresource Technology Reports	6	5	6	1.25	91
Biocatalysis and Agricultural Biotechnology	5	4	4	1.33	24
Computers & Industrial Engineering	4	4	4	2.00	27

Source: Authors, with data generated in Bibliometrix

duction and *Science of the Total Environment*) perform a stronger role in concentrating the work that defines the field's intellectual center of gravity. If one wants to understand how CE is being incorporated into agrifood RD&I, this distinction is crucial: the field is being expanded in one editorial space and, to a significant extent, validated or sharpened in another.

This asymmetry indicates that the field operates through a division of editorial roles. Some journals primarily function as vehicles for the broad dissemination of new research, whereas others play a more selective role in concentrating the studies that progressively shape the field's conceptual architecture. This reflects the coexistence of exploratory expansion and progressive intellectual consolidation, two complementary dynamics commonly observed in emerging scientific domains. As new research areas expand, scientific production tends to diffuse across a broad range of publication outlets, while a smaller group of journals progressively concentrates the contributions that exert greater conceptual influence on the field [60, 61, 65, 70].

At first glance, the geographic distribution of publications suggests a relatively democratized field. Countries such as *India* (27 publications), *Pakistan* (8), and *Malaysia* (7) appear prominently, alongside *Brazil*, *Nigeria*, and *China*. This differs from the more traditional concentration patterns observed in other areas of environmental or technological research.

But once production is crossed with influence, a different hierarchy appears. Analyzing country publication frequency, total citations, and average article citations conjunctly enables a comprehensive assessment of national scientific contributions by integrating publication output with both overall and average citation impact, thereby supporting more informative cross-country comparisons of research performance [71, 72]. In Table 4, *Cameroon* stands out with 202 total citations, followed by *Australia* (121), *Spain* (57), *India* (49), and *Germany* (29). The corresponding average article citations are even more revealing: *Australia* = 121, *Spain* = 28.5, *Germany* = 9.7, while *India* = 8.2 and *China* = 3.5.

Cameroon's position as an extreme outlier is largely explained by the fact that one of the co-authors of the highly cited review by Onyeaka et al. [73] is affiliated with an institution in that country. The study explores the potential of artificial intelligence to reduce food waste and support circular economy strategies through improved resource efficiency and lower environmental impacts. Because of its exceptional citation performance, this single publication substantially increases Cameroon's citation indicators despite the country's comparatively limited scientific output in the field.

Collaboration patterns introduce complexities to the further scenario. The network includes 604 country links, but these are not evenly distributed. A small number of corridors, namely, *China–India*, *China–USA*, *Italy–Spain*, among others, concentrate a disproportionate share of collaborative ties. Meanwhile, countries like *Germany* appear less frequently in absolute terms but are fully embedded in international collaboration (100% multi-country publications).

Taken together, these patterns suggest that the field is neither centralized nor fully globalized. It is better described as polycentric and selectively connected, with multiple regional poles linked through strategic collaborations. This matters because it shapes how CE is

Table 4 Countries' performances

Country	Freq	TC	Average Article Citations
Cameroon	1	202	202,00
Australia	1	121	121,00
Spain	4	57	28,50
India	27	49	8,20
Germany	3	29	9,70
Belgium	1	20	20,00
Sweden	3	9	9,00
Iran	3	8	4,00
Oman	1	8	8,00
Brazil	6	7	7,00
China	5	7	3,50
France	1	7	7,00
South Africa	4	3	1,50
Greece	4	1	1,00
Malaysia	7	1	1,00
Turkey	1	1	1,00

Source: Authors, with data generated in Bibliometrix

interpreted: different regions likely bring different priorities into the same conceptual space (e.g. resource constraints, technological capabilities, policy agendas).

This tells that recent CE in agrifood RD&I is geographically broad in terms of participation, but much less even in terms of recognized influence. Some countries function as volume producers, others as citation-efficient anchors, and still others remain present without having yet translated production into visibility. In a field organized through rapid expansion, this is not surprising. But it is analytically important, because it suggests that CE in agrifood RD&I is emerging through asymmetrical regional trajectories, each with different levels of consolidation and reach.

The implication is methodological as much as substantive. The geographic distribution of scientific production should not be interpreted as evidence that national innovation systems are converging toward a common circular transition trajectory. Rather, the bibliometric evidence suggests that the scientific knowledge base on CE in agrifood systems is expanding through geographically distributed but asymmetrically influential research communities, reflecting distinct institutional capacities, research priorities, and innovation trajectories. This interpretation is consistent with the literature on national innovation systems, which emphasizes that scientific and technological development tends to evolve through heterogeneous regional pathways rather than through uniform convergence [74–76]. Consequently, the field is better understood as a globally connected but structurally heterogeneous research domain, characterized by multiple regional entry points into circular agrifood innovation rather than by a single internationally convergent knowledge trajectory.

In Table 5 is presented the temporal analysis of keyword frequency. It enables the identification of the emergence, persistence, and evolution of research topics, providing insights into changing thematic priorities and recent trends within the scientific field [61, 65]. If there is one point in which the structure of the field becomes unmistakable, it is in the conceptual network. Circularity is its umbrella, but not yet a settled paradigm. The frequency data already points to a strong core, i.e. *circular economy* (672 occurrences) dominates the vocabulary, followed by *sustainability* (205), *waste* (109), and *agriculture* (94). But the co-occurrence structure adds to the crucial layer that these terms are tightly interconnected.

The network metrics confirm this (see Fig. 4). The keyword co-occurrence network identifies the conceptual structure of the research field by revealing groups of frequently associated topics, thereby highlighting the principal thematic domains and their interrelationships

Table 5 Keywords frequency timespan 2023:2026

Keywords	2023	2024	2025	2026	% 2026/2023
Life Cycle Assessment (LCA)	18	63	119	134	644,44%
Sustainability	29	91	179	205	606,90%
Anaerobic Digestion	13	42	76	86	561,54%
Agriculture	15	40	80	94	526,67%
Waste Management	15	39	76	87	480,00%
Circular Economy	123	285	582	678	451,22%
Waste	22	45	98	119	440,91%
Sustainable Development	24	55	102	114	375,00%
Management	23	55	86	98	326,09%
Agricultural Waste	23	44	74	85	269,57%

Source: Authors, with data generated in Bibliometrix

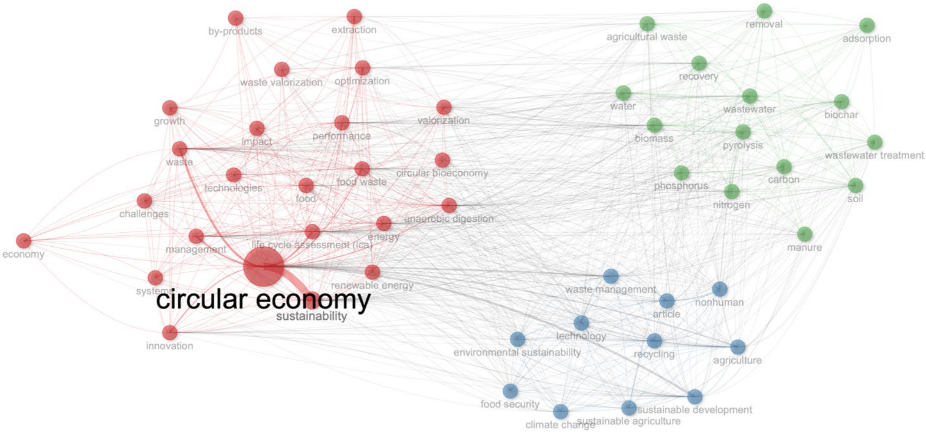

Fig. 4 Keywords co-occurrence clusters. Source: Authors, with data generated in Bibliometrix

within the scientific literature [61, 65]. *Circular economy* has the highest centrality and betweenness. It acts as a hinge term, linking otherwise distinct domains. Around it, a dense constellation of terms emerges, highlighting *management*, *performance*, *innovation*, *life cycle assessment*, *food waste* and *energy*.

Three things stand out here. First, the field is not structured around one narrow technology. Second, the CE agenda in agrifood RD&I is being articulated simultaneously through normative vocabulary (*circular economy*, *sustainability*, *sustainable development*), managerial/evaluative vocabulary (*management*, *performance*, *LCA*), and material-process vocabulary (*waste*, *anaerobic digestion*, *biomass*, *waste management*). Third, equally important is what remains outside the conceptual core. Although digital agriculture-related Technologies (including artificial intelligence, blockchain-enabled traceability, and Agriculture 4.0/5.0) were deliberately incorporated into the search strategy, they do not occupy central positions in the co-occurrence network. Rather than structuring the field, these technologies appear only marginally, indicating that their relevance within circular economy-oriented agrifood RD&I remains considerably more aspirational than empirically consolidated. That triad tells us that circularity in this literature is being assembled as a hybrid research language that joins environmental aspiration, operational management, and technological application.

This configuration leads to an important analytical insight. The field is fragmented because the center is too inclusive. Circular economy operates as a broad integrative label under which different problematics coexist, sometimes without full conceptual alignment.

This configuration suggests that the incorporation of CE into agrifood RD&I has been driven primarily by well-established practical demands within the sector [20], particularly those related to biomass valorization, waste recovery, and resource efficiency [34]. Rather than reflecting the emergence of a clearly defined new technological paradigm, the evidence points to the convergence of previously established research agendas around a shared sustainability framework. From a research perspective, this finding highlights the need to strengthen approaches capable of more consistently integrating the technological, systemic, and organizational dimensions of the circular economy. From an RD&I policy perspective, it underscores the importance of promoting policy instruments that foster convergence among research agendas that remain only partially integrated [6, 23].

This becomes even clearer in the factorial analysis (see Fig. 5). Factorial analysis of keywords provides a low-dimensional representation of the conceptual relationships among research topics, facilitating the identification of underlying thematic structures and the intellectual organization of the field [61, 65]. Rather than multiple clearly separated clusters, the field appears as a single, densely populated conceptual space, within which themes such as *biomass*, *sustainable development*, *sustainability*, *LCA*, *anaerobic digestion*, and *agricultural waste* are embedded. This suggests that the literature analyzed has not yet differentiated into internally coherent paradigms. Instead, it remains aggregated around a shared vocabulary, within which different research traditions coexist.

The persistence of these themes within a shared conceptual space indicates that the literature continues to favor the accumulation of complementary knowledge over the specialization into clearly differentiated subfields. This pattern is consistent with a scientific domain that is still undergoing consolidation [60, 61], in which distinct research traditions remain connected by common concerns related to sustainability and circularity [27]. From this perspective, future research may contribute to the field's scientific maturity by developing integrative models that more effectively connect these different approaches within more coherent conceptual frameworks.

This finding reinforces the evidence obtained from the co-occurrence network. The latent conceptual structure of the field continues to be organized around biomass valorization, waste management, life cycle assessment, and sustainability-related themes, whereas digital technologies remain peripheral and do not yet constitute an autonomous or consolidated thematic domain.

The thematic map adds a second layer of structure, a clear distinction between centrality and density that allows us to separate what is important from what is developed. Interestingly, the strongest cluster is not *circular economy* itself, but *sustainable development*, which combines the highest Callon centrality (5.646) and the highest Callon density (21.549).

This finding is particularly significant because it indicates that the most mature and internally connected part of the field is not organized around circular economy as an autonomous research domain, but around a broader sustainability-oriented knowledge base within which

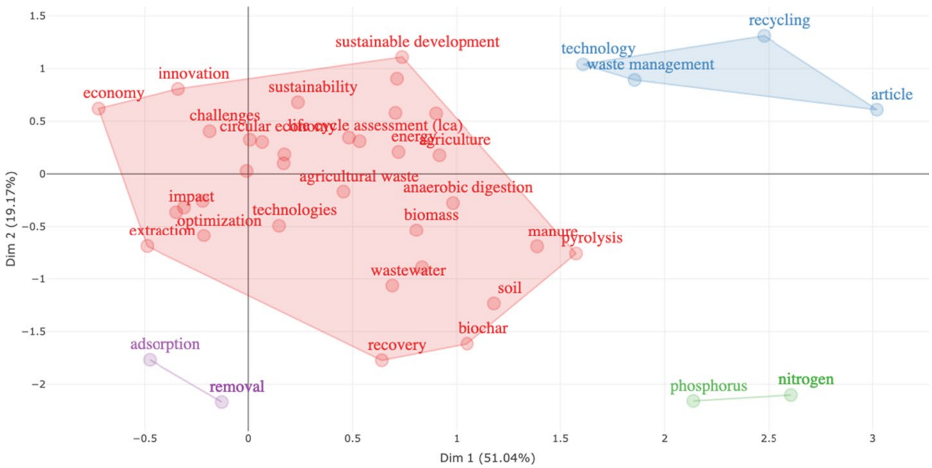

Fig. 5 Keywords factorial analysis. Source: Authors, with data generated in Bibliometrix

circular economy is conceptually framed and operationalized. This interpretation is consistent with previous studies showing that circular economy has primarily evolved as an operational framework supporting broader sustainability objectives rather than as an independent scientific paradigm [6, 27, 77].

By contrast, *circular economy* remains highly central (4.566) and large in frequency [2, 798] but is less internally dense than *sustainable development*. That means the cluster holds the field together and does not yet possess the same degree of internal specialization.

The applied clusters deepen the picture. *Biomass* has strong centrality (4.141) and substantial frequency (1, 391), showing that circular bioeconomy-type pathways are not peripheral applications but one of the main operational routes through which CE enters agrifood RD&I. *Anaerobic digestion*, by contrast, while important (444 occurrences), is much less central (2.319). It is a significant technical theme, but it does not define the field in the same way.

Recent study [78] demonstrates that integrated supply chain models can convert food waste into electricity, heat, and biofertilizers while simultaneously optimizing economic, environmental, and social objectives under a triple bottom line framework. These systems often incorporate life cycle assessment (LCA) as a core analytical tool, enabling the evaluation of environmental impacts across all stages of the supply chain (from waste collection to energy generation and by-product recovery) [78]. This reinforces the interpretation that circularity in agrifood RD&I is strongly articulated through bioenergy pathways, particularly those grounded in resource recovery and biomass valorization.

These positions allow a more precise interpretation of the field's dominant orientation. The thematic map presented in Fig. 6 supports the interpretation of the conceptual structure of the research field by classifying keyword clusters according to their degree of interaction with the overall research domain (centrality) and their internal development (density), thus distinguishing well-established, transversal, specialized, and emerging research themes [65, 79, 80]. The field's main thematic architecture (see Fig. 6) remains anchored in *sustainability*, *CE* as master frame, and *biomass*-related material recovery/valorization. This suggests that the current literature incorporates circularity above all through efficiency-oriented and resource-centered pathways. More transformative, systemic, or socio-technical agendas are present, but they have not yet displaced this central configuration.

This result also helps explain the limited structural relevance of digital agriculture-related technologies observed throughout the conceptual analyses. Although these technologies are frequently associated with future circular transitions in strategic and policy narratives, the present bibliometric evidence indicates that they have not yet become one of the dominant scientific trajectories within agrifood circular economy research.

This thematic hierarchy indicates that the field remains primarily organized around resource-efficiency and biomass valorization strategies rather than broader system redesign. Although more transformative, regenerative, and socio-technical perspectives are present, they still occupy a secondary position within the conceptual architecture of the literature. This pattern is consistent with recent evidence showing that circular economy in agrifood systems has largely evolved through incremental resource recovery, waste valorization, and process optimization, whereas more systemic transition approaches remain comparatively less developed [6, 20, 34]. Consequently, *circular economy* currently appears less as a disruptive paradigm replacing existing agricultural innovation models than as an organizing framework through which established sustainability concerns are progressively being rearticulated.

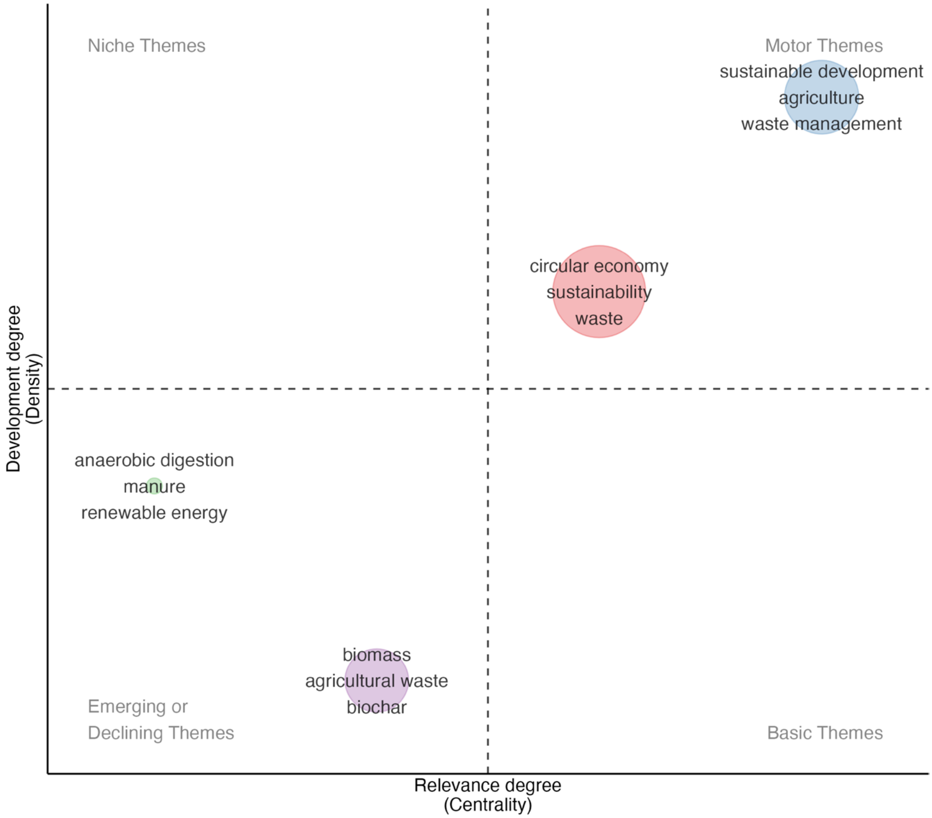

Fig. 6 Keywords thematic map. Source: Authors, with data generated in Bibliometrix

This finding has important implications for the formulation of both research agendas and public policies. The predominance of themes centered on resource efficiency and resource valorization suggests that circular economy has been incorporated primarily as a mechanism for improving existing processes [20, 27], rather than as a driver of systemic transformation in agrifood systems [6, 20, 30]. In this context, RD&I policies can play a key role by fostering research aimed at integrating circularity, organizational innovation, and regenerative transitions, thereby extending the scope of the current predominantly operational approaches [81, 82].

The thematic evolution map (see Fig. 7) provides a longitudinal view of the conceptual development of the research field by identifying the continuity, emergence, divergence, and convergence of keyword clusters across successive periods, thereby elucidating the evolution of the field's intellectual structure [61, 65, 80]. The most stable trajectory is the persistence of "circular economy" across all periods, with strong continuity indices (above 0.7). This confirms that CE has not been replaced by competing frameworks, but there is continuity. In earlier periods, the CE core includes a mix of waste, management, and sustainability terms. Over time, it incorporates a broader set of elements, like digital transformation, drivers and barriers, supply chain, carbon footprint.

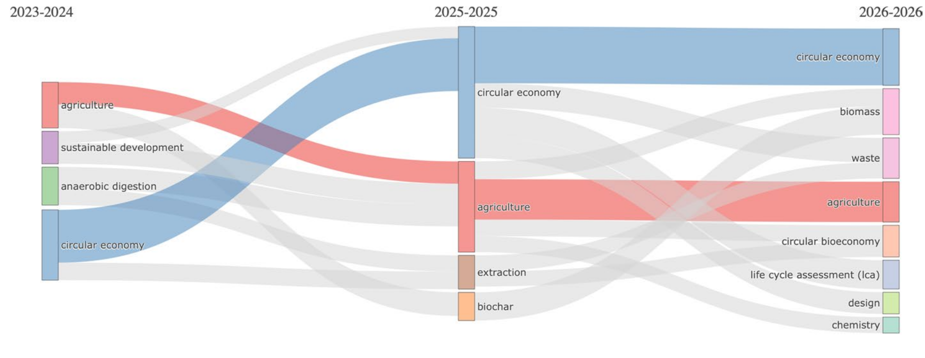

Fig. 7 Keywords thematic evolution. Source: Authors, with data generated in Bibliometrix

A second trajectory moves from circular economy toward agriculture-specific terms, food security, soil, renewable energy and bioeconomy. What indicates a gradual anchoring of CE within agricultural research contexts. A third trajectory connects biomass-related themes to agriculture and extraction processes, bringing in biotechnology, fermentation, lignocellulosic biomass, and biofuel.

This constitutes perhaps the clearest bibliometric evidence that circular bioeconomy pathways have become one of the principal operational interfaces through which circular economy is being incorporated into agrifood RD&I-related scientific production. This interpretation is consistent with recent studies showing that biomass valorization, biorefineries, and the productive reintegration of agricultural residues have become central mechanisms for translating circular economy principles into innovation processes within agrifood systems [34, 83, 84].

Revealing evidence comes from the thematic evolution. Here, technologies appear embedded within broader CE trajectories, as part of supply chains, sustainability transitions, or agricultural systems. It is important because they do not appear as independent organizing themes. Yet digital technologies do not dominate the frequency rankings. In the trend topics analysis, the strongest signals remain tied to management and food waste, not to AI or blockchain.

The thematic stability observed over time suggests that circular economy has evolved beyond an emerging topic to become an organizing framework for recent scientific production [6, 27]. However, the gradual expansion of associated themes indicates that this consolidation has occurred through the progressive incorporation of new research agendas [60, 65], rather than through the replacement of existing ones. This pattern highlights opportunities for future research to explore still underdeveloped interfaces among circularity, technological innovation, and the systemic transformation of agrifood systems [81, 82].

What emerges from these trajectories is a process of layered evolution. The field retains its core while progressively incorporating new concerns. The question of technology requires more careful reading than simply listing keywords. Digital agriculture, AI, and blockchain do appear, but how they appear is what matters.

The temporal series points to a sharp increase in production over the period. The vocabulary associated with the field also grows rapidly. In Table 5, *circular economy* rises from 123 occurrences in 2023 to 678 in 2026; *sustainability*, from 29 to 205; *life cycle assessment*

(LCA), from 18 to 134; *waste*, from 22 to 119; *management*, from 23 to 98; *agriculture*, from 15 to 94; *anaerobic digestion*, from 13 to 86; and *agricultural* waste, from 23 to 85. This indicates that CE in agrifood RD&I has become a rapidly expanding area of organized scientific attention.

Among this tenth major keywords we have terms that grew more than 500% from 2023 to 2026: *Life Cycle Assessment (LCA)* (18 → 134), *Sustainability* (29 → 205), *Anaerobic Digestion* (13 → 86), and *Agriculture* (15 → 94).

However, growth alone says little unless it is interpreted against the field's internal organization. The key point is that this expansion has not produced a single settled paradigm. Instead, what we observe is the enlargement of a research space whose internal agenda is becoming denser but remains distributed across partially overlapping thematic fronts. Taken together, these patterns indicate that the field has progressed beyond its formative stage but has not yet reached conceptual stabilization. Rather than converging toward a single dominant paradigm, the available evidence suggests the consolidation of a broad, increasingly diversified, and rapidly expanding research arena in which multiple circular agrifood innovation trajectories continue to coexist [20, 77, 85].

Recent review studies increasingly recognize artificial intelligence, blockchain, IoT, and other digital technologies as enabling technologies for future circular transitions in agrifood systems, particularly by supporting traceability, resource optimization, and supply-chain integration [82, 86]. However, the present bibliometric evidence indicates that these technologies have not yet become structural pillars of the scientific field. Instead, they currently occupy a peripheral position within the dominant conceptual architecture, suggesting that their scientific incorporation still lags behind their growing strategic prominence in policy and innovation debates.

In Table 6 we have the combined presentation of keyword frequency and the first quartile (Q1), median, and third quartile (Q3) publication years provides a comprehensive characterization of research topics by jointly capturing their prevalence and temporal evolution, thereby facilitating the identification of emerging, persistent, and mature themes within the scientific field [65, 80]. It can be seen that *blockchain technology* appears with only 7 occur-

Table 6 Keywords trend topics

Keywords	Frequency	Year (Q1)	Year (Median)	Year (Q3)
Circular Economy	678	2024	2025	2025
Sustainability	205	2024	2025	2025
Life Cycle Assessment (LCA)	141	2024	2025	2025
Management	98	2024	2024	2025
Food Waste	72	2024	2024	2025
Article	60	2023	2024	2025
Environmental Economics	16	2023	2023	2024
Animals	14	2023	2023	2024
Animal	13	2023	2023	2024
Agricultural Economics	8	2025	2026	2026
Sustainable Food Systems	8	2025	2026	2026
Blockchain Technology	7	2024	2026	2026

Source: Authors, with data generated in Bibliometrix

rences, while *sustainable food systems* and *agricultural economics* also appear late and with low frequency. In Table 5, *AI*, *blockchain*, or *precision farming* do not appear among the top-ranking dominant terms. If the analysis stopped there, one might conclude that emerging technologies remain marginal. That conclusion would be too superficial.

The joint examination of Tables 5 and 6 together reveals a structural asymmetry between what anchors the field and what is actively reconfiguring it over time. In the frequency distribution, the conceptual core is unmistakably concentrated around a small set of terms: *circular economy* (678 occurrences), *sustainability* (205), *life cycle assessment* (141), *waste* (119), *sustainable development* (115), *management* (98), and *agriculture* (94). These values are not only higher in absolute terms. They also indicate a relatively stable semantic backbone through which CE is articulated in agrifood RD&I.

However, when these results are contrasted with the temporal patterns in Table 6, a different layer of the field becomes visible. Terms such as *management* (98 occurrences, with peak activity concentrated in the 2024–2025 window) and *food waste* (72), similarly concentrated in the mid-period) exhibit strong temporal clustering. While more recent but lower-frequency entries, such as *blockchain technology* (7 occurrences), appear only in later time slices. The key point is that the terms dominating the field structurally are not the same ones driving its temporal variation. Instead, the field evolves through shifts in a secondary layer of themes, while its core vocabulary remains largely intact.

This divergence between high-frequency terms and high-momentum topics is analytically meaningful because it clarifies the mechanism through which circular economy is being incorporated into agrifood RD&I. The persistence of dominant terms such as *circular economy* (678) and *sustainability* (205) alongside the temporal emergence of more specific topics suggests that the field is not undergoing conceptual substitution, but rather incremental recomposition.

New themes progressively attach to the conceptual core. The limited presence of technologically oriented terms in the trend analysis, such as *blockchain technology* (7), confirms that digital technologies still occupy a structurally peripheral position in the field, although recent review studies increasingly identify them as important enablers of circular transitions in agrifood systems [86]. Rather than constituting consolidated research fronts, they currently indicate emerging research trajectories. By contrast, the stronger temporal visibility of terms such as *management* (98) and *food waste* (72) indicates that the literature continues to be primarily organized around operational, governance, and resource-efficiency concerns, consistent with recent evidence showing that these themes remain the dominant organizational axis of circular economy research in agrifood systems [18].

Taken together, these two tables show that the evolution of the field is best understood as a process of densifying a stable conceptual core while selectively incorporating new thematic elements, rather than as a shift toward an entirely new organizing paradigm.

This leads to a nuanced conclusion. The field is incorporating emerging technologies, but in a subordinate and integrative way. Digital tools function as enablers within existing circularity frameworks, not as drivers that redefine the structure of the field.

Seen as a whole, the evidence points in a consistent direction. The field is expanding rapidly and globally, but without a corresponding consolidation of its conceptual core. *Circular economy* has become the dominant reference point, yet it operates as a broad umbrella rather than a sharply defined paradigm. Within this umbrella, research is organized around *efficiency*, *resource management*, and *sustainability*, with *biomass* pathways playing a central operational role.

At the same time, new elements are entering the field (e.g. *digital technologies*, *bio-economy transitions*, *supply chain innovations*), but they do so from the margins inward, gradually reshaping the agenda without yet displacing its core.

This already tells us that CE has been incorporated into agrifood RD&I, above all, by resource recovery, performance assessment, waste management, biomass valorization, and sustainability framing.

The thematic evolution analyses indicate that digitalization- and innovation-oriented concerns are gradually becoming more visible within the circular economy agenda for agrifood systems. This movement is consistent with recent review studies that identify artificial intelligence, blockchain, Industry 4.0 technologies, and digital platforms as emerging enablers of circular transitions in agrifood systems [82, 86], although their effective incorporation into the scientific core of the field remains limited. They do so, however, in a subordinate way. Because they are embedded in established circularity trajectories rather than displacing them. Emerging technologies are structurally secondary but increasingly consequential.

So, we have a combination of a strong circularity core, a sustainability-driven thematic hierarchy, biomass as operational bridge, and digital technologies as still-subordinate but rising connectors. This analytical discovery allows the answer to the paper's central problem: the incorporation of CE into agrifood RD&I has occurred through a hybrid and uneven reconfiguration of the scientific knowledge base, in which efficiency, sustainability, biomass valorization, and emerging technological mediation are being assembled into a still-evolving architecture.

Conclusion and Future Directions

This study set out to examine how the circular economy (CE) has been incorporated into the scientific domain of agrifood research, development, and innovation (RD&I) to interrogate the conceptual structure, thematic evolution, and dominant orientations that have shaped this interface. The evidence generated demonstrates that, although CE has become an increasingly visible reference in agrifood RD&I, its integration into agrifood RD&I remains fragmented, and frequently anchored in process-specific or efficiency-oriented approaches rather than in systemic reconfigurations of innovation agendas.

From a theoretical standpoint, the main contribution of the study lies in reframing the CE–agrifood relationship through the lens of RD&I as a knowledge-producing and direction-setting domain. The results suggest that the recovered literature has not converged toward a unified conceptual model capable of consistently articulating circularity principles with technological innovation trajectories. Instead, what emerges is a pattern of partial convergence, in which CE appears simultaneously as (1) a normative framework (2), a set of technological solutions (often centered on waste valorization and resource efficiency) and (3) an analytical layer supported by system-level assessment tools.

However, these dimensions remain only loosely integrated, indicating that circularity has been more frequently operationalized as incremental improvement within prevailing production logics. Saying in other form: circularity has not been operationalized as a driver of transformative innovation. This finding advances the scientific literature by clarifying that the central challenge is not the absence of CE-related research, but the limited consolidation of CE as a structuring principle of agrifood RD&I itself.

One of the main findings of this study is the disconnect between the strategic prominence attributed to digital agriculture-related technologies and their actual position within the scientific structure of circular economy-oriented agrifood RD&I. Although artificial intelligence, blockchain, and Agriculture 4.0/5.0 are frequently presented as drivers of future circular transitions, the current literature remains predominantly organized around resource recovery, biomass valorization, waste management, and life cycle assessment. This suggests that digital technologies presently represent an emerging expectation for the field rather than one of its consolidated research frontiers.

Practically, these results carry direct implications for the design and governance of agrifood RD&I systems. The persistence of efficiency-driven and technology-centric orientations suggests that current innovation efforts may be insufficient to support broader transitions toward circular and regenerative production models. In this context, aligning agrifood RD&I agendas with CE principles requires a shift from isolated technological solutions toward integrated strategies that simultaneously address material flows, system performance, and innovation directionality.

This implies the need to (a) embed circularity criteria into research prioritization processes, (b) strengthen the connection between technological development and system-level outcomes, and (c) promote coordination across different stages of agrifood value chains. The bibliometric patterns identified in this study indicate that such alignment is still incipient and uneven across regions and thematic areas, reinforcing the importance of targeted policy and institutional interventions.

From a practical and managerial perspective, for policymakers, research and development (R&D) organizations, and other agrifood stakeholders, the findings of this study reinforce that research, development, and innovation (RD&I) constitutes a strategic mechanism for accelerating the transition of the circular economy from a predominantly normative concept to technological solutions effectively embedded in agrifood systems. The results show that recent scientific production has been structured primarily around biomass valorization, resource recovery, waste management, and life cycle assessment, whereas more systemic approaches and emerging technologies still occupy a relatively peripheral position. This configuration provides objective evidence of both the areas in which the field has achieved greater scientific maturity and the knowledge gaps that continue to require investment in research and innovation.

For policymakers, these findings provide an empirical basis for guiding funding priorities, public support programs, and regulatory instruments aimed at advancing the circular economy in agrifood systems. Rather than supporting all initiatives broadly classified as circular, the evidence highlights the importance of fostering research agendas that strengthen the integration of resource recovery, digital technologies, systemic performance assessment, and regenerative approaches, thereby reducing the thematic fragmentation currently observed in the scientific literature. The findings may also support the development of official monitoring indicators, evaluation criteria for public innovation programs, and investment prioritization mechanisms targeting areas in which the scientific literature demonstrates greater potential for technological consolidation.

For researchers and R&D organizations, the findings identify concrete opportunities for shaping future research agendas. In particular, the bibliometric analysis reveals considerable scope for strengthening research that integrates circular economy with artificial intelligence, blockchain, digital agriculture, and other emerging technologies, as well as studies aimed at combining different circular strategies within agrifood systems. Likewise, the identification of leading collaboration networks, influential journals, established research themes, and emerging topics may contribute to the development of scientific partnerships, the internationalization of research activities, and the design of research agendas that are more closely aligned with the knowledge gaps identified in this study.

For farmers, cooperatives, agribusiness firms, and other stakeholders, the findings indicate which technologies and strategies currently exhibit the highest levels of scientific maturity and practical applicability. The predominance of studies focused on biomass valorization, waste reutilization, resource efficiency, and life cycle assessment suggests opportunities for cost reduction, product diversification, the creation of new revenue streams, improved operational efficiency, and enhanced competitiveness. At the same time, the relatively limited presence of digital technologies and regenerative approaches points to areas in which both public and private organizations can direct innovation efforts to enhance economic, environmental, and social value creation across agrifood systems.

At the same time, the findings highlight that the advancement of CE in agrifood RD&I is constrained by conceptual fragmentation and the absence of integrative analytical frameworks (not only by technological limitations). This reinforces the need for approaches that explicitly connect technological innovation with broader system transformations, particularly in relation to resource efficiency, waste reintegration, and the redesign of production and supply chain configurations. In this sense, the study contributes by providing an empirically grounded basis for understanding where literature currently stands and where its main structural gaps lie.

Future research should build on these insights by advancing three main directions. First, there is a need for studies that explicitly integrate CE with RD&I theoretical frameworks, moving beyond descriptive or sector-specific analyses toward models that explain how circularity shapes innovation trajectories over time. Second, further research should explore the dynamics through which agrifood technological solutions evolve into system-level transformations towards circularity, particularly by examining the interaction between emerging technologies, institutional arrangements, and value chain reconfigurations. Third, greater attention should be given to the heterogeneity observed across regions and thematic domains, investigating how different socio-economic and institutional contexts influence the incorporation of CE into agrifood RD&I.

Additionally, future work would benefit from qualitative and case-based analyses, enabling a more detailed understanding of how circularity is operationalized in practice and how it influences decision-making processes within agrifood RD&I systems. Such efforts are essential to move from the current state of partial and fragmented integration toward a more coherent and actionable framework for circular agriculture.

The limitations of this study are primarily associated with the bibliometric review protocol adopted, which relies on predefined search strategies, database selection criteria, and filtering procedures to construct the analyzed corpus. Consequently, the use of different databases, search strings, inclusion criteria, or filtering strategies may lead to partially different results. In addition, the analysis was intentionally restricted to peer-reviewed articles published in English and indexed in the selected international databases. Although this criterion contributed to enhancing the methodological consistency and comparability of the analyzed corpus, it may have excluded relevant studies published in other languages or indexed in alternative databases. Furthermore, this bibliometric review focused primarily on the quantitative analysis of publication data and bibliometric indicators. While this approach is particularly well suited to identifying patterns of scientific production, collaboration networks, conceptual structures, and thematic evolution, it does not provide an in-depth assessment of the methodological quality, theoretical depth, or contextual interpretation of individual studies. Future research may therefore compare the present findings with those obtained using alternative bibliometric protocols, broader database coverage, different search strategies, or multilingual datasets. In addition, complementary Systematic Literature Reviews (SLRs) could provide a more comprehensive qualitative assessment of the available evidence, thereby validating, refining, and extending the findings reported in this study.

Taken together, the bibliometric indicators analyzed in this study show that the development of circular economy in agrifood RD&I has been driven primarily by themes related to sustainability, biomass valorization, waste management, and resource efficiency [6, 20, 34]. This configuration suggests that the scientific evolution of the field has initially been shaped more by the expansion and integration of established research agendas than by the emergence of new technological or organizational paradigms. Consequently, future research agendas and innovation policies may focus on promoting approaches that integrate these different dimensions within more systemic and regenerative perspectives [81, 82].

In summary, this study demonstrates that while CE has gained significant traction within agrifood RD&I, its incorporation into agrifood RD&I remains structurally incomplete. By identifying the conceptual patterns and asymmetries that characterize this integration, the article provides a foundation for both theoretical refinement and practical reorientation of agrifood innovation systems toward more genuinely circular and regenerative configurations.

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Declarations

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Authors and Affiliations

Marcos Antonio Gomes PenaJr. [2] · **Sérgio Saraiva Nazareno dos Anjos** [1] · **Fabrício Oliveira Leitão** [2]

✉ Marcos Antonio Gomes Pena Jr.
marcospenajr@gmail.com; marcos.pena@embrapa.br

[1] Embrapa Agroenergy - Parque Estação Biológica (pqEB), PqEB s/n, Ed. Embrapa Agroenergia, Brasília, DF Caixa Postal 40.315, CEP.: 70770-901, Brazil

[2] University of Brasília (UnB), Brasília, Brazil