

Circular Biomaterials: A Bibliometric Analysis

Loso Judijanto¹, Dila Padila Nurhasanah²

¹ IPOSS Jakarta, Indonesia

² Universitas Nusa Putra

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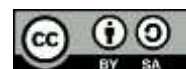
VOSviewer

Waste Valorization

ABSTRACT

This study presents a bibliometric analysis of research on circular biomaterials to map its intellectual structure, thematic evolution, citation impact, and collaboration patterns. Bibliographic data were retrieved from the Scopus database and analyzed using VOSviewer through keyword co-occurrence, overlay, and density visualizations, supported by citation, co-authorship, institutional, and country-level analyses. The results show that the field is organized around a circular economy pole that links biomaterials with sustainability, food waste, lignocellulosic biomass, biofuel, and 3D printing, and a biomedical pole that connects biomaterial with biocompatibility, tissue regeneration, and controlled animal studies. A dense agro-industrial waste and biopolymer cluster bridges both poles, confirming waste valorization as the main pathway through which biomaterials enter circular systems. The overlay analysis indicates a shift from early work on 3D printing and material characterization toward recent studies on tissue regeneration, lignocellulosic valorization, and agricultural applications. The most cited documents focus on additive manufacturing, agro-industrial biowaste valorization, and microbial bioconversion. Collaboration networks remain small and fragmented, consisting of single-team author and institutional clusters and limited international links centered on Nigeria and Malaysia. The study highlights circular biomaterials as a young and multidisciplinary field that requires stronger integration between circular economy principles, material engineering, and biomedical applications.

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Corresponding Author:

Name: Loso Judijanto

Institution: IPOSS Jakarta

Email: losojudijantobumn@gmail.com

1. INTRODUCTION

The transition from a linear take-make-dispose economy toward a circular economy has become a central agenda of global sustainability efforts, as dependence on fossil-based resources continues to intensify climate change, resource depletion, and plastic pollution. Within this transition, biomaterials, understood as materials that are

fully bio-based and biodegradable, are increasingly positioned as a practical alternative to petrochemical materials because they can be produced from renewable resources and returned safely to natural cycles at the end of their life [1]. Biomaterials such as biopolymers are expected to reduce reliance on fossil resources, lower carbon emissions, and support resource-efficient production systems [2]. As a result, biopolymers and

biomaterials are now regarded as strategic components of circular economy policies and industrial applications [3].

A defining characteristic of circular biomaterials is their close relationship with waste valorization. Agro-industrial biowaste, previously treated merely as a disposal problem, is now viewed as a resource that can be converted into value-added biomaterials through chemical, biological, and microbial routes [4], [5]. Agricultural residues such as corn waste and corn cob have been used to develop biomaterials whose sustainability can be evaluated from a life-cycle perspective [6], [7]. Likewise, food waste biomass has been explored as a feedstock for biomaterials within circular economy frameworks [8], [9], including bio-based products enriched with biostimulant agents for horticultural practices [10].

Beyond agricultural and food residues, the feedstock base of circular biomaterials continues to diversify. Lignocellulosic biomass is being valorized for integrated biofuel and biomaterial production [11], while microalgae are recognized as renewable biological resources for diversified bioproducts [12]. Non-wood forest resources [13], shea butter waste [14], and plant wastes [15] further illustrate how regional biomass streams can be transformed into biomaterials that support local circular bioeconomies. These developments show that circularity in biomaterials is not limited to a single material or sector but spans agriculture, forestry, food processing, and energy systems.

Circular biomaterials are also increasingly linked to advanced manufacturing and biomedical engineering. Additive manufacturing enables biomaterials to be printed on demand with minimal material waste, making 3D printing a promising route toward sustainable and circular production [16], including the fabrication of orthopedic implants [17]. In the biomedical field, byproducts such as silk sericin [18] and tilapia skin [19] are being upcycled into biomaterials for tissue repair and regeneration, reflecting an emerging waste-to-health perspective. Recent reviews further emphasize the expanding range of

biomaterial and biopolymer applications in circular economy contexts [20], while studies in innovation management, textile design, and science education show that circular biomaterials also involve organizational, creative, and educational dimensions [21], [22], [23].

The rapid growth and multidisciplinary nature of this literature call for a systematic overview of its development. Bibliometric analysis is a quantitative approach for examining scientific literature that can reveal publication trends, influential works, collaboration networks, leading institutions and countries, and thematic evolution within a research domain [24]. Compared with a narrative review, bibliometric mapping offers a broader picture of the intellectual structure of a field and shows how research themes are connected and how they change over time.

Although studies on circular biomaterials are increasing, the literature remains scattered across material science, environmental engineering, biotechnology, medicine, and design. Existing studies generally address specific feedstocks, processing routes, or applications, so the overall structure of the field, its main thematic clusters, its most influential documents, and its collaboration patterns have not been clearly mapped. This condition limits the ability of researchers and policymakers to understand how biomaterials contribute to circular economy transitions and which directions deserve further attention. Therefore, this study conducts a bibliometric analysis of circular biomaterials research to map its intellectual structure, thematic evolution, citation impact, and collaboration networks.

2. METHODS

This study employed a bibliometric analysis approach to examine the scientific development of circular biomaterials research. Bibliographic data were retrieved from the Scopus database, which was selected because of its broad coverage of peer-reviewed literature across science,

engineering, medicine, and the social sciences. The search combined the terms “circular” and “biomaterial” or “biomaterials”, and the records were exported in RIS format in September 2026. The dataset comprised journal articles, reviews, book chapters, a book, and conference papers published between 2015 and 2026. The extracted information included titles, abstracts, author and indexed keywords, authors, affiliations, year of publication, source titles, and citation counts. The records were screened for relevance, and a retraction notice contained in the dataset was not treated as a substantive contribution in the citation analysis.

Bibliometric mapping was performed using VOSviewer, a software tool widely used to construct and visualize bibliometric networks [25]. VOSviewer was applied to generate network maps based on keyword co-

occurrence, co-authorship among authors, institutional collaboration, and country-level collaboration. The network visualization was used to identify thematic clusters and the most central concepts, the overlay visualization was used to trace the temporal evolution of research themes based on the average publication year of each keyword, and the density visualization was used to distinguish intensively studied themes from emerging or marginal topics. In addition, the most cited documents were identified from the Scopus citation counts to determine the most influential works in the field.

3. RESULTS AND DISCUSSION

3.1 Keyword Co-Occurrence Network Visualization

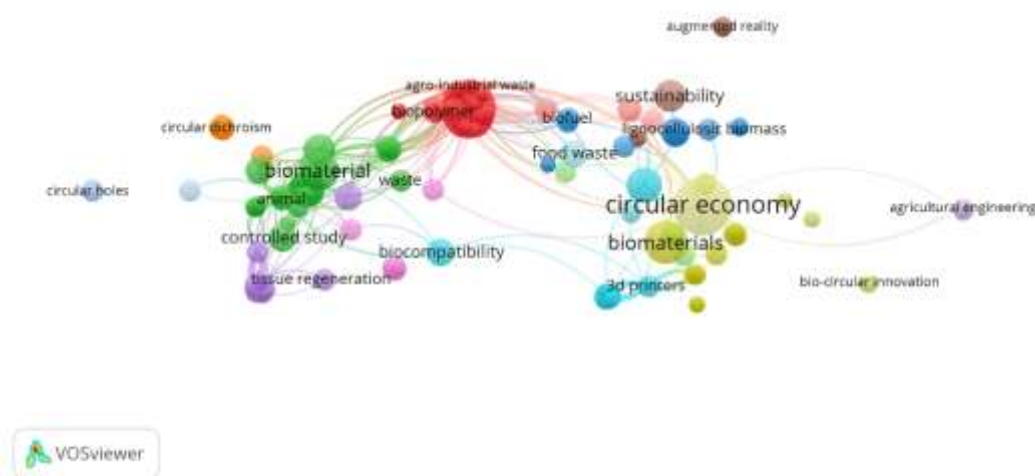


Figure 1. Network Visualization

Source: Data Analysis, 2026

Figure 1 illustrates the intellectual structure of circular biomaterials research. The largest and most central node is “circular economy”, followed by “biomaterials” and “biomaterial”, indicating that the literature is built primarily around the integration of biomaterials into circular economy frameworks. The map is arranged into two

main poles, a circular economy pole on the right and a biomedical–biological pole on the left, which are connected through a dense agro-industrial waste cluster in the center. This configuration shows that the field combines sustainability-oriented and life-science-oriented research streams, with waste

valorization acting as the main bridge between them.

The red cluster, centered on “agro-industrial waste” and “biopolymer”, is the densest part of the network. Its tightly packed nodes represent studies on converting agricultural, industrial, and food residues into biopolymers and value-added biomaterials through fermentation, extraction, and microbial bioconversion [4], [5]. The numerous links from this cluster to both poles confirm that biowaste valorization is the most integrative theme in the field. The neighboring blue and light blue nodes, including “biofuel”, “lignocellulosic biomass”, and “food waste”, extend this theme toward biorefinery approaches that jointly produce energy and materials [8], [11]. The yellow, cyan, and brown clusters on the right side form the circular economy pole. The yellow cluster links “circular economy” and “biomaterials” with “bio-circular innovation”, reflecting conceptual and innovation-oriented studies [21]. The cyan cluster connects “3d printers” with “biocompatibility”, representing research on the additive manufacturing of biomaterials for sustainable products and medical implants [16], [17]. The brown cluster, containing “sustainability” and the separated node “augmented reality”, reflects sustainability assessment and educational applications of biomaterials [1], [23], while “agricultural engineering” appears as a peripheral node that links circular biomaterials with agricultural systems [6], [7].

The green and purple clusters on the left represent the biomedical and biological dimension of the field. The green cluster includes “biomaterial”, “animal”, “controlled study”, and “waste”, which are typical indexed terms of experimental and preclinical studies, while the purple cluster is centered on “tissue regeneration”, reflecting the regenerative use of upcycled byproducts for tissue repair [18], [19]. The small orange and light steel blue nodes, “circular dichroism” and “circular holes”, are located at the periphery with weak links, indicating that part of the dataset uses the term “circular” in a spectroscopic or geometric sense rather than in the circular economy sense [26], [27]. Comparable uses of the term appear in studies on circular RNA therapeutics, circular intestinal defects, and circular endoscopic resection [28], [29], [30], which are associated with the animal and controlled-study terms in this area of the map.

Overall, the network reveals a field organized into three interconnected dimensions: circular economy and sustainable manufacturing (right), waste valorization and bioprocessing (center), and biomedical applications (left). The relatively sparse links between the left and right poles show that the integration of circular economy principles into biomedical biomaterials is still limited, while the peripheral position of terms carrying a non-economic meaning of “circular” highlights the need for careful keyword filtering in bibliometric studies of this topic.

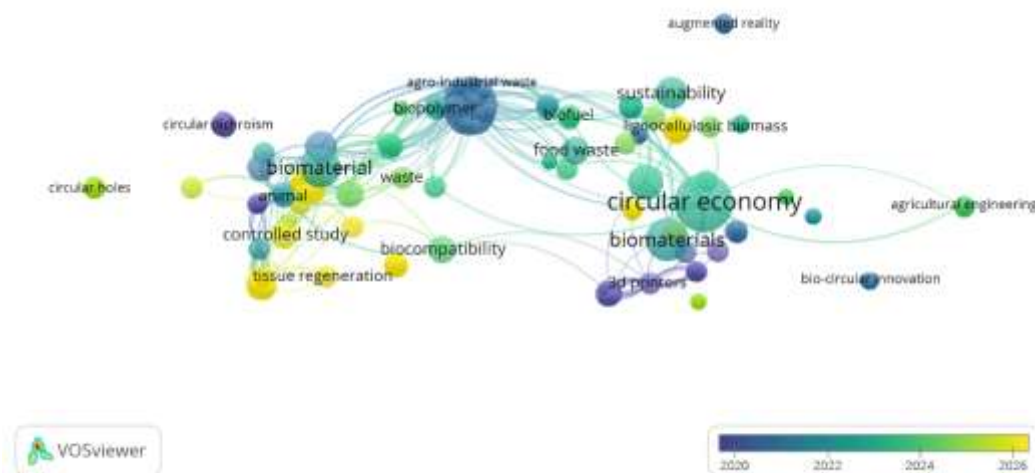


Figure 2. Overlay Visualization

Source: Data Analysis, 2026

Figure 2 presents the overlay visualization of circular biomaterials research, in which node colors represent the average publication year of each keyword, ranging from 2020 (purple) to 2026 (yellow). The central node “circular economy” appears in teal, corresponding to approximately 2023, confirming that the circular framing of biomaterials research has become dominant only in recent years. The dense agro-industrial waste and biopolymer cluster is shown in blue, around 2021, indicating that biowaste valorization was one of the earliest foundations of the field.

The temporal pattern reveals a clear progression. The earliest themes, colored purple, are “3d printers”, the nodes surrounding “biomaterials”, and “circular dichroism”, reflecting initial work on additive manufacturing and material characterization [16], [17], [26]. The middle period, around

2022–2023, is dominated by “sustainability”, “food waste”, “biofuel”, and “biomaterial”, marking the expansion of research toward sustainability assessment and food waste valorization [1], [8]. The most recent themes, shown in green to yellow, include “tissue regeneration”, “controlled study”, “lignocellulosic biomass”, “agricultural engineering”, “waste”, and “biocompatibility”, pointing to growing interest in regenerative medicine and lignocellulosic valorization [11], [18], [19].

The overlay visualization therefore indicates that circular biomaterials research is a young and still-evolving field. The shift from manufacturing- and characterization-oriented studies toward biomedical regeneration and advanced biomass valorization suggests that the field is moving from industrial sustainability toward health-related and higher-value applications.

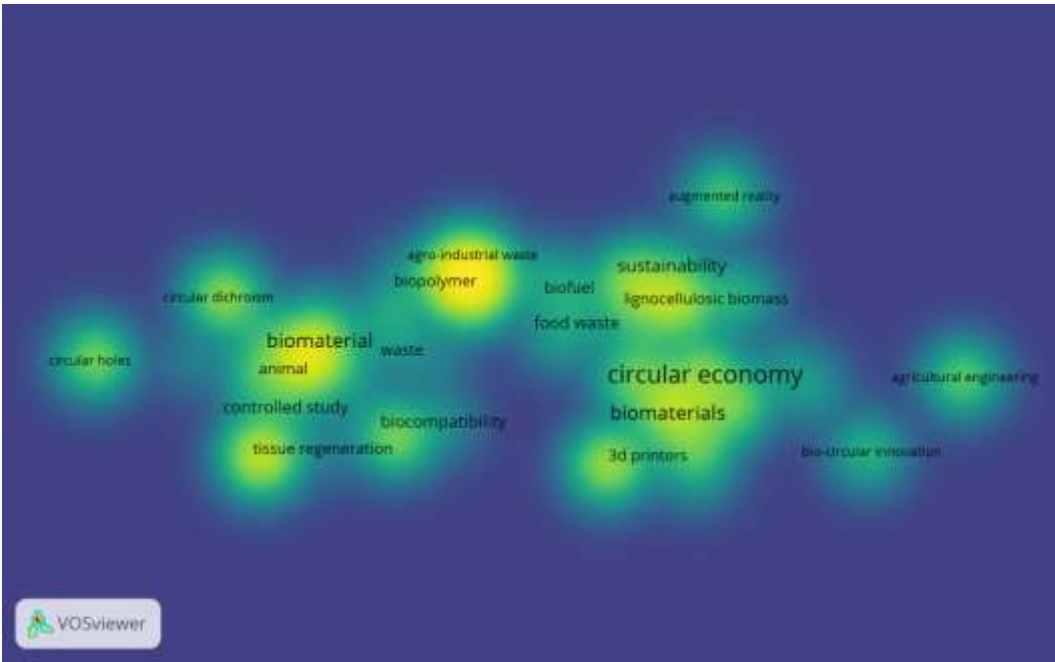


Figure 3. Density Visualization
Source: Data Analysis, 2026

Figure 3 shows that research on circular biomaterials is concentrated in several distinct hot spots rather than in a single dominant core. The brightest areas are located around “agro-industrial waste” and “biopolymer”, “biomaterial” and “animal”, and “circular economy” and “biomaterials”, indicating that biowaste-based biopolymers, biomedical biomaterials, and circular economy framing are the most intensively studied themes. Additional high-density zones appear around “sustainability” and “lignocellulosic biomass”, “tissue regeneration”, and “3d printers”, reflecting well-developed subthemes related to biomass valorization, regenerative applications, and additive manufacturing.

In contrast, lower-density regions are found around “augmented reality”, “bio-circular innovation”, “agricultural engineering”, “circular dichroism”, and “circular holes”. These peripheral areas represent emerging or marginal topics that have received limited attention, including educational, innovation-management, and agricultural engineering perspectives. The separated distribution of the hot spots also indicates that the field remains fragmented, with each thematic core developing relatively independently, which opens opportunities for studies that connect circular economy principles with the biomedical and engineering applications of biomaterials.

3.2 Citation Analysis

Table 1. Top Cited Documents

Citations	Authors and Year	Title
204	[26]	Terahertz circular dichroism spectroscopy of biomaterials enabled by kirigami polarization modulators
118	[16]	3D printing with biomaterials: Towards a sustainable and circular economy
116	[4]	Valorization of agro-industrial biowaste to biomaterials: An innovative circular bioeconomy approach

96	[5]	Bioconversion of agro-industry sourced biowaste into biomaterials via microbial factories – A viable domain of circular economy
95	[17]	3D printable biomaterials for orthopedic implants: Solution for sustainable and circular economy
56	[3]	Biopolymers and biomaterials for special applications within the context of the circular economy
53	[7]	Turning agricultural wastes into biomaterials: Assessing the sustainability of scenarios of circular valorization of corn cob in a life-cycle perspective
23	[1]	Biomaterials and Regenerative Agriculture: A Methodological Framework to Enable Circular Transitions
18	[10]	Food Waste-Derived Biomaterials Enriched by Biostimulant Agents for Sustainable Horticultural Practices: A Possible Circular Solution
17	[23]	Circular Species: Designing critical thinking into children's science education through biomaterials and augmented reality

Source: Scopus, 2026

3.3 Co-Authorship Analysis

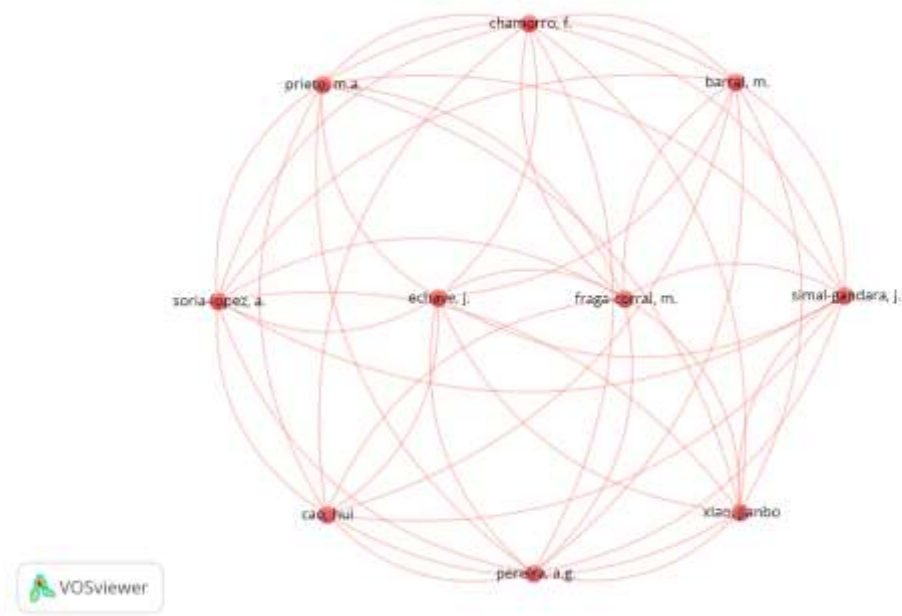


Figure 4. Author Visualization
Source: Data Analysis, 2026

Figure 4 displays the co-authorship network of circular biomaterials research, which consists of a single, fully connected cluster of ten authors: Echave J., Fraga-Corrall M., Pereira A.G., Soria-Lopez A., Barral M., Chamorro F., Prieto M.A., Simal-Gandara J., Cao Hui, and Xiao Jianbo. All nodes have similar sizes and are linked to one another, indicating that the cluster originates from a single collaborative work on the valorization

of food waste biomass and biomaterials from a circular economy perspective [8]. The team brings together researchers from Spain, Portugal, and China, reflecting an international collaboration in food science and nutrition. The absence of other connected author groups in the map shows that co-authorship in this field is still limited to isolated teams, and no stable multi-publication author network has yet emerged.

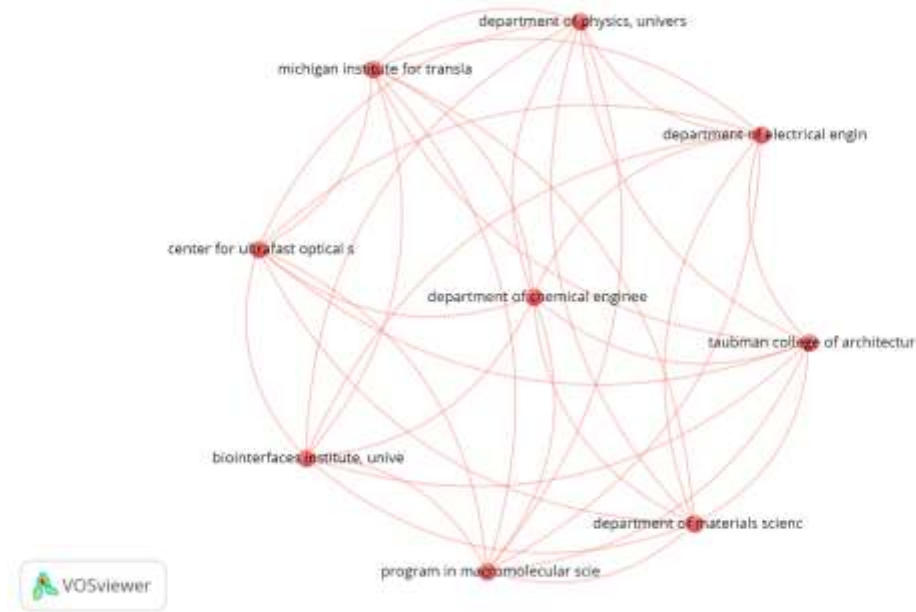


Figure 5. Institution Visualization

Source: Data Analysis, 2026

Figure 5 presents the institutional collaboration network, which is also formed by a single, fully interconnected cluster of nine units belonging to the University of Michigan, United States, namely the Department of Materials Science and Engineering, the Department of Physics, the Center for Ultrafast Optical Science, the Department of Electrical Engineering and Computer Science, the Department of Chemical Engineering, the Taubman College of Architecture and Urban Planning, the Program in Macromolecular Science and Engineering, the Biointerfaces Institute, and

the Michigan Institute for Translational Nanotechnology. This structure derives from the highly cited study on terahertz circular dichroism of biomaterials [26], which combined expertise from physics, engineering, materials science, and architecture. The pattern demonstrates strong intra-university interdisciplinary collaboration, but it also shows that the institutional network in this dataset is shaped by a single highly cited document rather than by sustained collaboration among multiple institutions working on circular biomaterials.

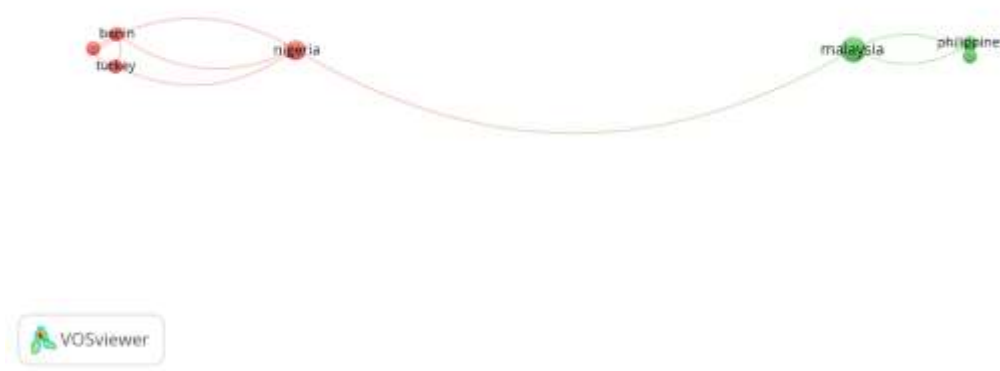


Figure 6. Country Visualization

Source: Data Analysis, 2026

Figure 6 shows the country collaboration network, representing the largest connected set of countries linked through co-authorship. Two clusters are visible. The red cluster is led by Nigeria and connects Benin, Turkey, and Canada (the unlabeled node), reflecting joint work on circular economy initiatives in the forest-based bioeconomy [13]. The green cluster is centered on Malaysia and includes the Philippines and Singapore (the unlabeled node), originating from collaborative research on the microbial bioconversion of agro-industry biowaste [5]. Both clusters are bridged by the Nigeria–Malaysia link, which stems from joint research on shea butter waste valorization [14], so that Nigeria and Malaysia act as the main connecting hubs. Other international partnerships, such as Spain–Portugal–China [8] and the United States–United Kingdom–Chile [1], form smaller separate components and therefore do not appear in the map, while countries such as India and Italy contribute mainly through domestic teams. This pattern indicates that international collaboration in circular biomaterials research remains limited and is largely driven by partnerships involving

developing economies in Africa and Southeast Asia.

4. CONCLUSION

The bibliometric analysis of circular biomaterials research reveals a young, rapidly developing, and highly multidisciplinary field built on the integration of biomaterials into circular economy frameworks. Its intellectual structure is organized around three connected dimensions, namely circular economy and sustainable manufacturing, agro-industrial waste valorization and bioprocessing, and biomedical applications, with waste-derived biopolymers serving as the main bridge between sustainability-oriented and life-science-oriented research. The thematic evolution shows a shift from early studies on 3D printing and material characterization toward sustainability assessment, food waste and lignocellulosic valorization, and, most recently, tissue regeneration and agricultural applications, while the citation analysis confirms that additive manufacturing and biowaste valorization form the core knowledge base of the field. However, co-authorship, institutional, and country networks remain small and fragmented, dominated by single-

document teams and limited international links centered on Nigeria and Malaysia. Future research should strengthen cross-disciplinary and international collaboration, connect circular economy principles more

explicitly with biomedical biomaterials, and apply more precise keyword filtering to distinguish circular economy studies from unrelated uses of the term “circular”.

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