Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-18

DOI: *10.15244/pjoes/216343* ONLINE PUBLICATION DATE: 2026-03-04

Original Research

Biodegradable Plastics in Soil: A Scientometric Analysis of Their Status, Evolution, and Future Research Directions

Menghao Yang[1], Meiling Jing[2]*, Shijun Chao[1, 3]**

[1]College of Eco-Environmental Engineering, Qinghai University, Xining 810016, China
[2]Key Laboratory of Biotechnology and Analysis and Test in Qinghai–Tibet Plateau, College of Ecological Environment and Resources, Qinghai Nationalities University, Xining 810007, China
[3]Qinghai Research and Design Institute of Environmental Sciences, Xining 810007, China

Received: 06 September 2025
Accepted: 02 January 2026

Abstract

The use of biodegradable plastics (BDPs) is increasingly recognized as a promising approach for mitigating plastic pollution in agricultural soils, but the environmental impacts of these materials in soil systems remain unclear. In recent years, publications in this field have multiplied, producing a large but disconnected body of knowledge. Such dispersion makes it difficult to form an integrated view of research progress. To address this gap, we conducted a scientometric analysis of 519 English-language publications (2005-2024) indexed in the Web of Science Core Collection. We mapped the structures of studies on BDPs in soil systems at institutional and regional scales. The results show that existing research is focused on three key pillars: materials science, agricultural application, and environmental behavior. Research has shifted from performance and degradation studies to critical evaluations of long-term ecological risks. This study presents potential emerging frontiers, such as interactions between BDPs and soil, innovative functional materials, and socioeconomic considerations. Theoretically, the research structure and its evolution are elucidated. Practically, this study provides researchers, policymakers, and industry stakeholders with useful information to inform decision-making and promote sustainable agricultural practices.

Keywords: biodegradable plastics, soil ecosystem, scientometrics, VOSviewer, CiteSpace

Introduction

Plastics owe their widespread adoption to features that render them suitable for many different uses [1]. For example, their water resistance, sealing ability, and moldability make them ideal for food and beverage packaging [2]. Moreover, their light weight and notable durability render them suitable for the production of manufacturing components in industry [3]. In agriculture, plastics provide insulation, retain moisture, and suppress weeds, making them vital as crop-covering films that increase yield and quality.

*e-mail: ajml@163.com
**e-mail: chaoshijun@163.com

In medicine, their biocompatibility and capacity for sterilization enable large-scale production of disposable syringes and infusion bags [4]. In summary, it is difficult to envision modern life without plastics [5]. As reported by Plastics Europe, global plastic production reached 413.8 million tons in 2023 and is projected to exceed 500 million tons by 2050. These statistics underscore the essential role of plastics in industrial applications, everyday activities, and the global economy.

Nevertheless, this notable dependence on plastic materials has led to significant environmental and resource-related concerns [6]. Most traditional plastics decompose at a very slow pace and remain in the environment for centuries or longer. As these materials deteriorate, they release microplastics and nanoplastics that are dispersed extensively through soil, water, and air, ultimately entering the food supply and potentially into human bodies. Moreover, plastic manufacturing relies mainly on fossil fuels, which require substantial consumption of oil and gas annually [7]. This reliance results in the depletion of finite natural resources and increases energy demand and greenhouse gas emissions, which in turn exacerbate global climate change.

Given these increasing environmental pressures, plastic management is a long-term challenge with major impacts on resource sustainability and climate stability [8]. In this context, biodegradable plastics (BDPs), such as polylactic acid (PLA), polyhydroxyalkanoate (PHA), and starch-based polymers, are promising alternatives to conventional fossil-based plastics. Soil, which constitutes a highly active part of the Earth's surface system [9], is essential for agriculture, supports terrestrial ecosystems, and contributes to sustainable human development. Moreover, soil serves as a key environmental medium for BDP applications. Increasing evidence reveals that the use of BDPs in soil can reduce the risk of plastic accumulation [10].

Firstly, in terms of chemical stability, traditional plastics such as polyethylene (PE) are based on a backbone composed of highly stable carbon-carbon bonds. These bonds are resistant to microbial invasion. In contrast, BDPs like PLA are designed with hydrolyzable ester bonds that are prone to cleavage [11]. Secondly, when considering degradation pathways, traditional plastics mainly experience abiotic fragmentation. This process is driven by UV radiation and mechanical stress, leading to the formation of persistent microplastics [12]. Conversely, BDPs are depolymerized by extracellular enzymes secreted by soil microorganisms, triggering a biotic process that converts polymer chains into metabolizable oligomers. Thirdly, regarding environmental fate, while traditional plastics accumulate as inert physical pollutants that might adsorb agrochemicals, BDPs are ultimately mineralized into carbon dioxide, water, and microbial biomass. Thus, in theory, they complete the cycle within the soil ecosystem [13] (Fig. 1).

Connecting effective plastic waste management with enhanced soil health provides new opportunities for

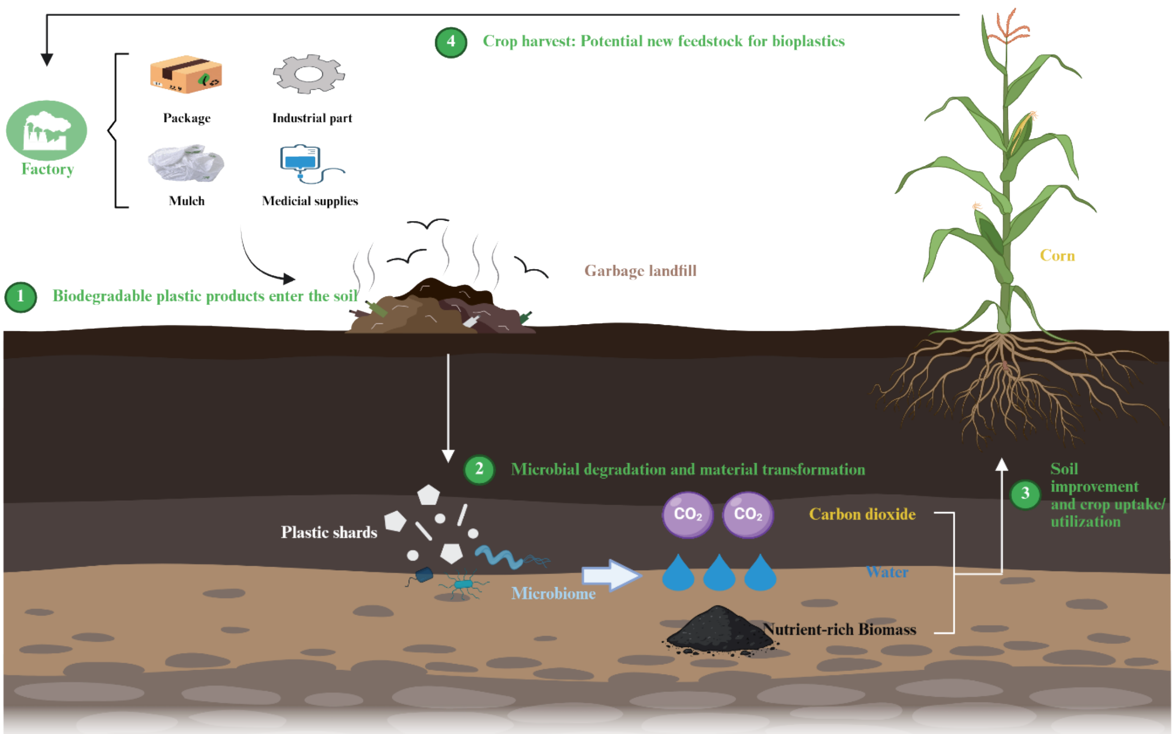

Fig. 1. Application pathway of BDPs in soil. (1) Entry of plastic products into the soil. (2) Microbial degradation and material transformation yielding carbon dioxide, water, and nutrient-rich biomass. (3) Improved soil structure and crop uptake/utilization. (4) Crop harvest as a potential new feedstock for bioplastics, closing the loop.

environmental stewardship [14]. Thus, research on the application and environmental impacts of BDPs in soil has become an expanding interdisciplinary field of study, attracting increasing attention from scholars in the fields of materials science, agronomy, and environmental science. However, the realization of these theoretical benefits in real-world soil environments is complex and controversial [15]. While BDPs exhibit potential for improving soil quality, key concerns regarding their degradation rates in different environments, the possible risk of degradation byproduct creation, and their long-term ecological effects remain and thus should be addressed through rigorous scientific evaluations. To assess both the benefits and the risks of BDPs, the current state of research must be understood [16]. Although many studies and narrative reviews exist, comprehensive, data-driven syntheses of the field's knowledge base, thematic evolution, and emerging trends are lacking. Traditional narrative reviews, which are often limited by subjective interpretation and narrow scope, are not suitable for mapping such large and fragmented studies [17]. Consequently, there is an urgent need to perform a scientometric analysis to systematically chart the intellectual landscape of BDPs within soil environments. The objective of this research is to explore the following key questions (RQs):

RQ1: What are the temporal and geographical trends of publication output and collaboration patterns in this field?

RQ2: What are the core research themes and the underlying intellectual structure of this domain?

RQ3: What are the emerging trends and key research frontiers that indicate future research directions?

The remainder of this work is organized as follows. "Materials and Methods" Section provides an outline of the data and methodologies. "Results" Section presents the research outcomes, including descriptive statistics, collaborative networks, co-citation patterns, and keyword analysis. "Discussion" Section offers an exploration of the implications of the findings, potential avenues for future research, and study limitations. Finally, "Conclusions" Section provides a summary of this study.

Materials and Methods

Data Sources

The literature data for this study were obtained from the Web of Science Core Collection (WoSCC). In the WoSCC, many high-impact journals are indexed, and it offers broad multidisciplinary coverage; the WoSCC is widely used in scientometric research [18]. Data were obtained on April 25, 2025, and the search period spanned from 2005 to 2024. The Boolean search query employed was as follows: (TS = ("biodegradable plastic*" OR "biodegradable polymer*" OR "compostable plastic*") AND TS = ("soil amendment*" OR "soil conditioner*" OR "soil quality" OR "soil health" OR "soil environment" OR decompos* OR "land application" OR mulch*) AND LA = (English) AND DT = ("Article" OR "Review")). This initial search returned 897 records that met the inclusion criteria. All the data comprised bibliographic metadata from a subscription database. Moreover, no human subjects or personal identifiers were involved.

The titles and abstracts of these publications were subsequently meticulously reviewed to ensure their high relevance to the research topic of this study. The exclusion criteria were primarily focused on the following two categories of literature that significantly deviated from reference [19] or were not very relevant to the research theme:

- Primary focus outside the BDP–soil nexus: Publications were excluded if their core topic pertained to aspects peripheral to the soil context, such as the synthesis, modification, or material characterization of BDPs, where the soil was mentioned only as a potential environment and not an actual application environment.
- Incidental or trivial mention: Publications were excluded if the interaction between BDPs and soil was merely a background statement or a secondary, trivial component of the research rather than a primary subject of investigation.

Following this screening process, a final dataset of 519 bibliographic records, comprising 453 original research articles and 66 review articles, was retained. The final dataset of the included literature was exported in "Plain Text File" format, and the record content was set to "Full Record and Cited References" [20].

Research Methods

We adopted a multimethod scientometric strategy [21] because it can be used to map large and fragmented studies and exhibits lower subjectivity than does the use of narrative reviews. The process encompassed five linked stages.

(1) Analysis of descriptive statistics: We quantified annual output and core journal sources to outline the field at the macroscopic level [22].

(2) Collaboration analysis: At the institutional and regional levels, we constructed collaboration networks to identify core academic communities and their geographic patterns [23].

(3) Co-citation analysis: We analyzed the authors and references to trace the knowledge base, identify foundational sources, and locate milestone studies.

(4) Keyword analysis: We performed cooccurrence and burst analyses to identify core topics and their ties and to show how topics have evolved [24].

(5) Synthesis and frontier exploration: We combined quantitative maps with qualitative readings of key clusters [25] to examine the context and knowledge structure of the field, proposed a conceptual framework for BDPs in soil, and identified limitations and priority

directions. The analytical framework and procedure are shown in Fig. 2.

A few records were dated to 2025 in CiteSpace because they were classified as early access at the time of collection. These articles were highly relevant and were retained to ensure coverage. This common artifact in bibliometric data did not affect our results or conclusions.

Analytical Tools

Two widely recognized visualization analysis software tools in the field of scientometrics [19], namely, VOSviewer (version 1.6.20) and CiteSpace (version 6.4.R1), were employed in this study.

VOSviewer [26], which was developed by van Eck and Waltman at Leiden University, the Netherlands, excels in producing clear, aesthetically appealing network visualizations and is particularly effective for mapping large-scale structural relationships. Thus, VOSviewer was applied in this study to construct collaboration networks among institutions and regions and a keyword cooccurrence network. This approach facilitated a robust delineation of the core academic communities, the global research landscape, and the primary thematic clusters within the field.

CiteSpace [27], which was developed by Professor Chaomei Chen at Drexel University, USA, is especially useful for identifying research frontiers and underlying knowledge bases over time. CiteSpace was employed primarily for co-citation analysis of authors and references to identify the foundational literature and milestone studies that shaped the domain. Furthermore, CiteSpace's specialized functions for keyword timeline analysis and burst detection were applied to trace the historical evolution of research topics and pinpoint the emerging trends that have garnered rapidly increasing academic attention [28].

Parameter Setting

To support rigor and replication, we configured the key parameters as follows. For VOSviewer networks (institutional, regional, and keyword cooccurrence), we employed full counting to assign equal weights to links [29]. We set minimum occurrence thresholds to highlight significant relations and improve clarity. Institutions and countries required ≥3 publications to be input into collaboration networks. Keywords required ≥5 occurrences to be input into the cooccurrence network. For CiteSpace co-citation and timeline maps, we set one-year time slices for the 2005-2024 period [30]. Within each slice, we used the g-index (k = 10) to select influential nodes. We applied "Pathfinder" and "Pruning Sliced Networks" to streamline the network structures. Cluster labels were generated with the log-likelihood ratio (LLR) method, which selects the terms that are statistically overrepresented within a cluster and

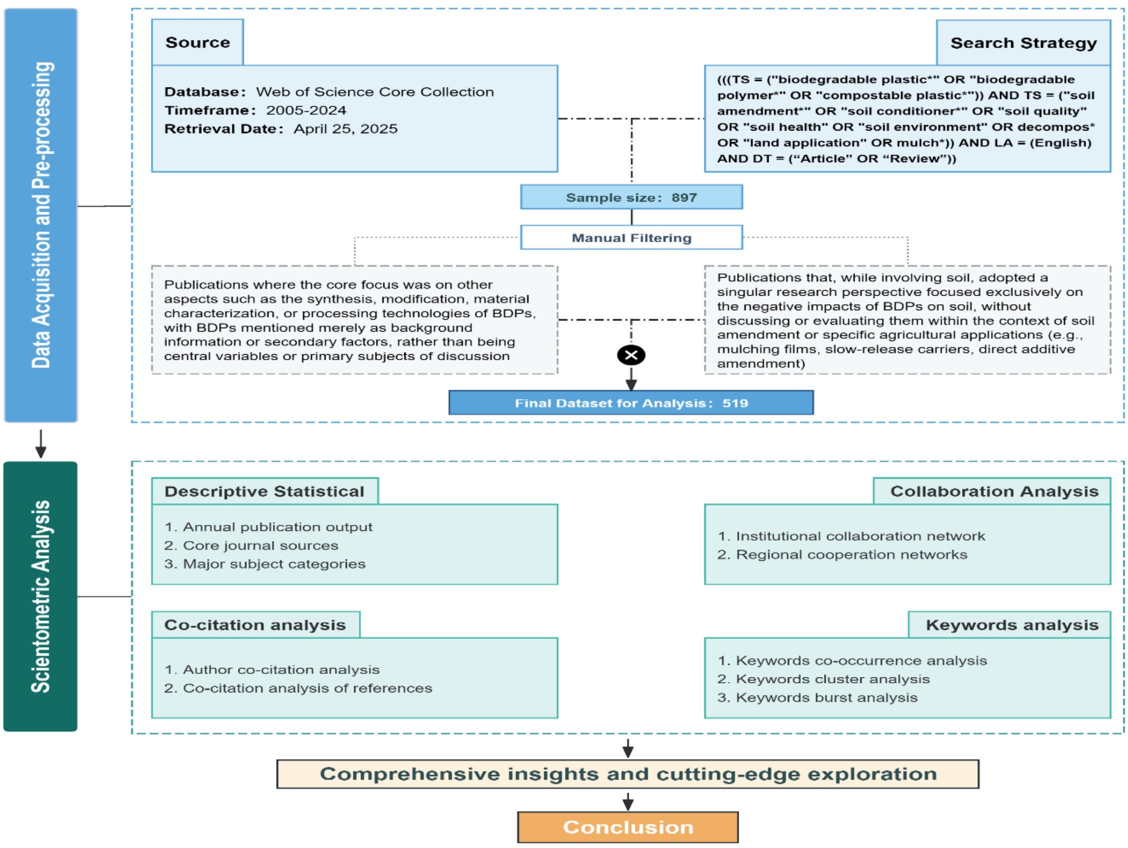

Fig. 2. Analytical framework and procedure of this study.

thus best capture its thematic content. Label sources comprised article titles for the author co-citation network and keywords for the reference co-citation network.

Results

Descriptive Statistical Analysis

Annual Publication Output

The annual number of publications serves as a key indicator for assessing the developmental trajectory of a given research field [31]. The output results of the research on the application of BDPs in soil over the past two decades are shown in Fig. 3, revealing a distinct three-stage growth pattern that illustrates its evolution from an emerging topic to a prominent research hotspot.

Initial Stage (2005-2011): This phase was characterized by preliminary exploration, with annual publication counts remaining in single digits and a cumulative total of only 28 articles. This sluggish growth was mainly due to significant technical and economic hurdles. Early-generation biodegradable polymers (mostly starch-based) had poor mechanical properties and unpredictable degradation rates. They often decomposed too quickly under field conditions. As a result, research focused mainly on polymer synthesis and characterization in materials science, with few successful applications in agronomy. Additionally, the absence of standardized international testing methods for soil biodegradability limited comparative research, keeping the field in an initial exploratory phase. The limited output can be attributed to two main contextual factors: the high costs and technical obstacles related to the industrial application of BDPs at that time, and a dominant research emphasis on proving biodegradability rather than assessing the potential of BDPs for soil enhancement.

Growth Stage (2012-2018): During this period, the field began to gain momentum, with the number of annual publications consistently exceeding 10 and peaking at 23 in 2016. This development was driven mainly by two key reasons. Scientifically, Rillig's seminal 2012 research on microplastic pollution heightened academic recognition of long-term soil contamination caused by leftover conventional plastic mulch, creating an urgent demand for sustainable alternatives. On the technological front, critical advances in modifying polymers through blending, particularly the successful market introduction of PLA/PBAT composites, addressed the earlier problem of excessive brittleness. This resulted in biodegradable mulch films with sufficient pliability for machine-based application in extensive farming. Aligning an ecological imperative with improved material performance shifted the focus of investigations from laboratory settings to large-scale, real-world testing.

Maturity Stage (2019-2024): Since 2019, the field has experienced rapid growth, with a sharp increase in the publication volume. The 396 articles published in these six years accounted for more than 76% of the total number of studies. This surge is heavily attributed to top-down policy interventions and global sustainability goals. Stringent regulations, such as the EU's Single-Use Plastics Directive and China's forceful "Opinions on Strengthening the Control of Plastic Pollution"

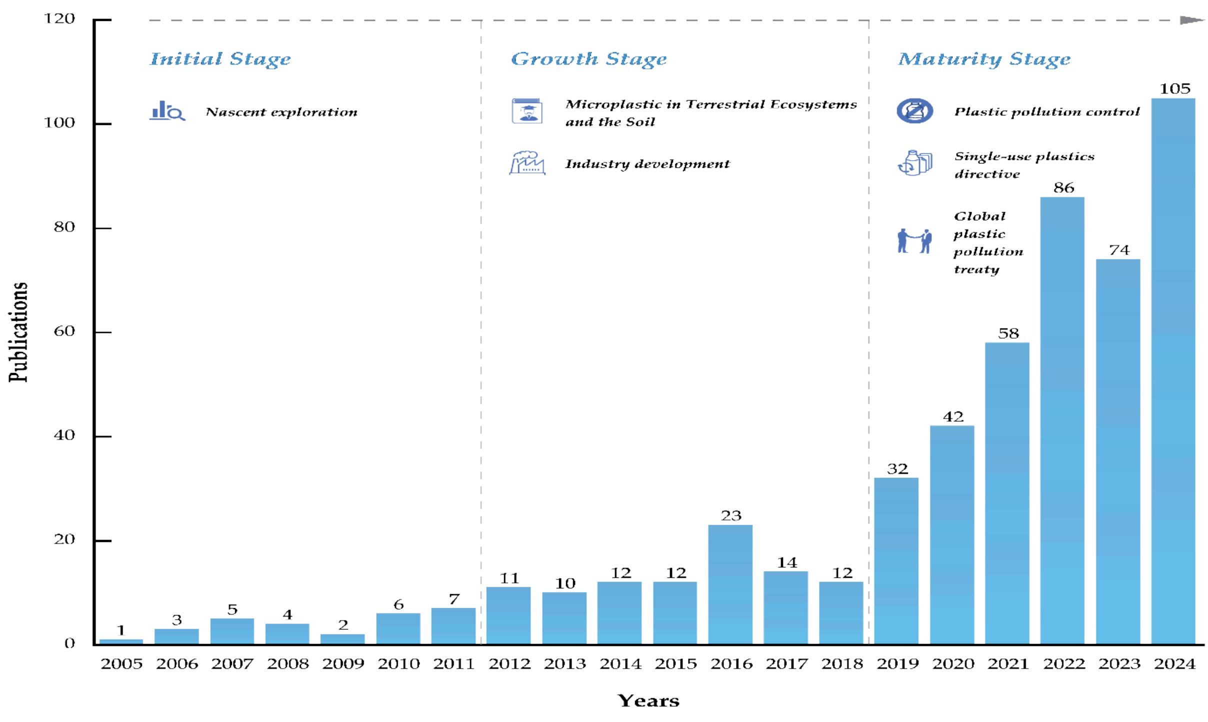

Fig. 3. Output of research on the application of BDPs in soil over the past 20 years.

(2020), created immense market demand and funding opportunities for agricultural BDPs. Additionally, the academic focus matured from simple efficacy testing to multidisciplinary deep dives – incorporating microbiome science, soil carbon cycling, and life-cycle assessment. This stage signifies that BDPs have transitioned from a niche material science topic to a central subject in global environmental governance and sustainable agriculture.

Core Journal Sources

Core journals are the main outlets for knowledge dissemination and academic exchange [32]. Analyzing their distributions helps identify the field's leading publication platforms and their interdisciplinary features [33]. In this study, core journals were defined operationally as the top 10 sources on the basis of publication count in our dataset. We report their citation impact for context. As indicated in Table 1, the top 10 journals published 163 articles (31.4% of all records), indicating a notable concentration of output.

Among these journals, Science of the Total Environment leads in both publication volume (41) and total citations (3500), making it a principal venue in this area. Importantly, publication counts do not necessarily track citation impacts [34]. For example, the Journal of Hazardous Materials is ranked fourth on the basis of publication count but second on the basis of total citations (1141) and exhibits the highest impact factor (11.3) among the listed journals. This pattern shows that a lower output can still be associated with greater influence. The relevant journals span environmental science (Science of the Total Environment and Environmental Pollution), polymer/materials science (Polymer Degradation and Stability and Journal of Polymers and the Environment), and agricultural science (Agronomy–Basel and Agriculture–Basel). This mix suggests that progress relies on integrating material innovation, environmental behavior assessment, and field-level validation. Overall, the output is concentrated in a small set of journals, and the field shows a clear interdisciplinary profile.

Collaboration Analysis

Institutional Collaboration Network

Scientific research institutions serve as key drivers of knowledge innovation [35]. An analysis of the collaboration network among institutions provides insights into the major patterns of knowledge exchange and resource sharing [36]. The institutional collaboration network generated using VOSviewer in this study is shown in Fig. 4.

The analysis revealed the presence of several tightly interconnected collaboration clusters, which exhibit clear regional characteristics [37]. The red cluster, which is centered on Washington State University, reflects leading North American institutions (e.g., the University of Tennessee), thereby forming the largest and most cohesive collaborative group in the field. Research on this topic has focused primarily on agricultural applications and field experiments. The blue and yellow clusters, which are anchored by the Chinese Academy of Sciences and the Chinese Academy of Agricultural Sciences, respectively, represent China's two major research hubs in this domain. These clusters are focused on environmental toxicity, degradation mechanisms, the practical application of degradable mulch, and soil improvement techniques. Notably, institutions such as Wageningen University serve as pivotal bridge nodes, linking geographically distinct clusters and highlighting the essential role of international collaboration in promoting global knowledge dissemination [38].

Regional Collaboration Network

Following the institutional collaboration patterns above, we examined collaborations at the country and

Table 1. Top 10 most productive journals on the application of BDPs in soil.

Rank	Journal	Publications	Percentage	Citations	Impact Factor (2024)
1	Science of the Total Environment	41	7.90%	3500	8.0
2	Polymer Degradation and Stability	20	3.85%	722	7.4
3	Polymers	18	3.47%	472	4.9
4	Journal of Hazardous Materials	15	2.89%	1141	11.3
5	Journal of Polymers and the Environment	15	2.89%	952	5.0
6	Environmental Pollution	13	2.51%	601	7.3
7	Agronomy–Basel	12	2.31%	187	3.4
8	Agriculture–Basel	11	2.12%	132	3.6
9	Journal of Applied Polymer Science	10	1.93%	154	2.8
10	ACS Sustainable Chemistry and Engineering	8	1.54%	174	7.3

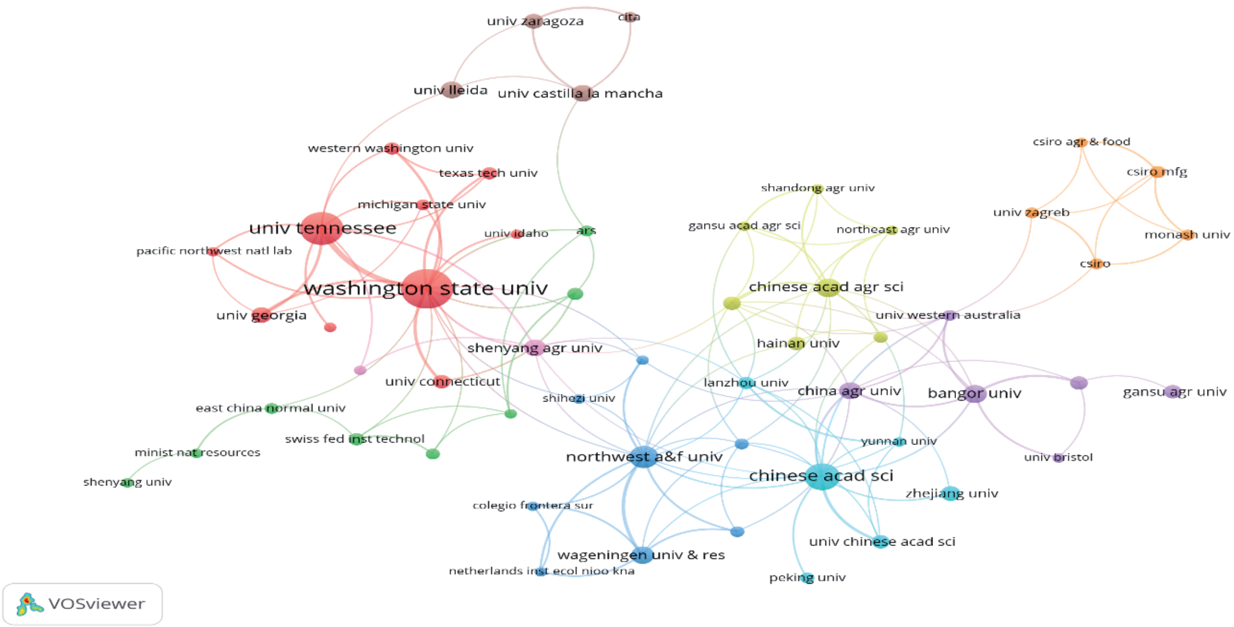

Fig. 4. Institutional collaboration network. Each node represents an institution, with the size of the node being proportional to its publication count. The lines between nodes indicate co-authorship links, and the thickness of the lines indicates the strength of the collaboration. Different colors represent distinct collaborative clusters identified by VOSviewer.

region levels to reveal the global research structure [39]. Table 2 provides a summary of the leading contributing countries on the basis of publication and citation count. The data reveal that China, the United States, and Italy lead in research output, producing 140, 102, and 51 publications, respectively, thereby comprising the primary group in terms of scholarly contribution. In terms of citations, China, the United States, and the Netherlands stand out, with 6894, 6798, and 2180 citations, respectively, indicating broad recognition. Some countries have a high number of citations per paper. For example, the Netherlands has only 16 papers but ranks third in terms of total citations (2180), suggesting high-impact contributions.

The regional collaboration network is shown in Fig. 5. The largest node and the thickest connecting line indicate strong cooperation between China and the United States. These two nations jointly serve as the central driving forces behind the advancement of the research area. Around this central axis, a European collaborative group led by Germany, Italy, and Spain, along with an Asia–Pacific network anchored by Australia and Japan, has developed into secondary regional centers. The visualization shows that high-impact countries such as the Netherlands mainly collaborate with key global players, including China, the United States, and European nations, which may account for the heightened visibility of their scholarly

Table 2. Top 10 most productive countries for the application of BDPs in soil.

Rank	Country	Publications	Citations	Average Citation/Publication
1	China	140	6894	49.24
2	USA	102	6798	66.65
3	Italy	51	1081	21.20
4	India	34	1630	47.94
5	Spain	33	1744	52.85
6	Australia	31	1849	59.65
7	Japan	29	715	24.66
8	Germany	28	1003	35.82
9	Poland	21	459	21.86
10	Netherlands	16	2180	136.25

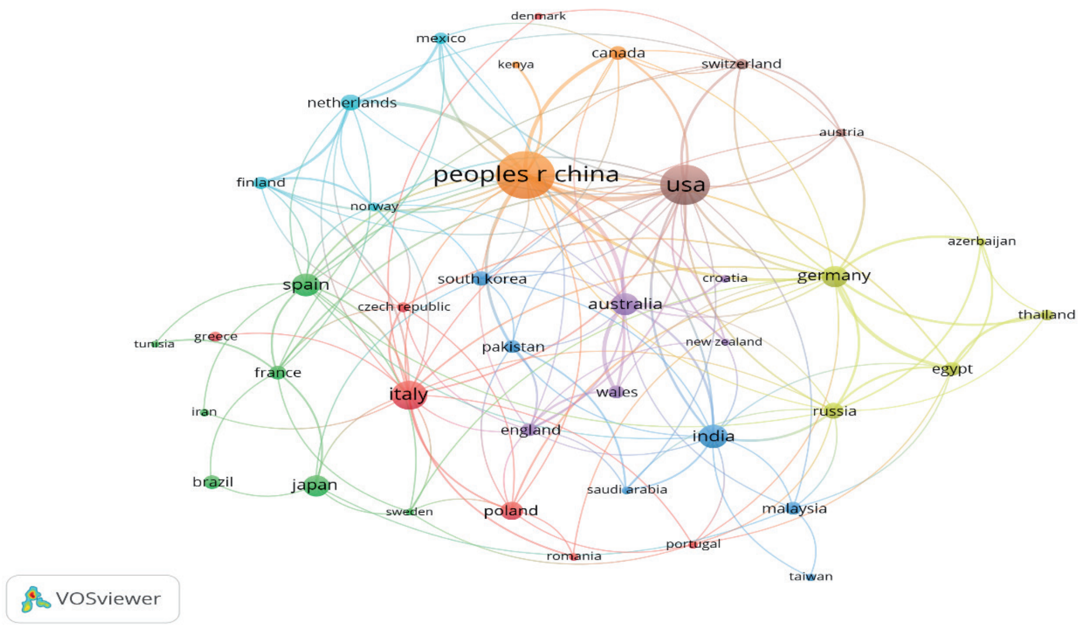

Fig. 5. Regional collaboration network. Each node represents a country/region, with the size of the node being proportional to its publication count. The lines between nodes indicate co-authorship links, and the thickness of the lines indicates the strength of the collaboration. Different colors represent distinct collaborative clusters identified by VOSviewer.

outputs. Overall, the network exhibits a hub-and-spoke shape led by China and the United States, with several regional hubs. Core knowledge creation and exchange remain concentrated in a small set of leading countries.

Co-citation Analysis

Author Co-citation Network

We conducted an author co-citation analysis to help identify well-known and influential scholars in the field [40]. The primary cited authors according to count and centrality are listed in Table 3. The analysis first highlighted a group of highly cited authors whose work forms the foundational knowledge base of the field. Kasirajan S (144) and Sintim HY (128) were identified as the most influential scholars in the field; their work constitutes a foundational component of the existing knowledge system. Kasirajan's key cited publication [41] emphasized the importance of transitioning from conventional PE mulch to biodegradable alternatives while highlighting economic cost and inconsistent performance as significant barriers to widespread adoption during that period. Sintim's notable research [42] examined the degradation behaviors of biodegradable mulches under various real-world soil and

Table 3. Top 10 cited authors ranked by count and centrality.

Rank	Cited Authors	Count	Centrality	Year
1	Kasirajan S	144	0.10	2013
2	Sintim HY	128	0.08	2018
3	Machado AAD	88	0.09	2019
4	Briassoulis D	86	0.06	2017
5	Steinmetz Z	86	0.32	2007
6	Qi YL	85	0.06	2020
7	Rillig MC	82	0.06	2018
8	Moreno MM	78	0.06	2013
9	Bandopadhyay S	76	0.02	2019
10	Kijchavengkul T	73	0.14	2012

composting conditions. These findings demonstrated that environmental climate factors greatly influence the multiyear breakdown process of biodegradable polymer materials.

Second, centrality helps identify bridging authors who link otherwise separate parts of the network [43]. For example, Steinmetz Z is fifth in terms of co-citation frequency but shows high centrality (0.32). His work [44] connects short-term agronomic benefits and long-term environmental concerns (e.g., microplastics and soil health), connecting multiple lines of inquiry.

Third, certain authors combine high co-citation counts with relatively low centrality, indicating authority within focused, recent subdomains. Notably, Machado AAD and Qi YL (2019-2020) fit this pattern. Machado's study [45] revealed that different types of microplastics can alter soil physical properties, with downstream effects on plant performance and microbial activity. Qi's work [46] focused on the rhizosphere and reported that plastic residues – particularly from BDPs – can shift the bacterial community and the profile of emitted volatile organic compounds, suggesting a pathway for plastic-plant interactions.

The author co-citation network is shown in Fig. 6. The network exhibits a high modularity value (Q = 0.6689) and a high average silhouette score (S = 0.9022), suggesting a clearly defined community structure and a high degree of internal homogeneity within the clusters. The major clusters can be interpreted as follows:

(1) Clusters #0 (biodegradable microplastics) and #9 (biodegradable plastic). Together, these two clusters comprise the core knowledge domain in this field. This area is focused on the following central issue: although BDPs are designed as alternatives to traditional plastics, their degradation can produce biodegradable microplastics (BDMPs), which may create new environmental risks. Cluster #9 mainly involves exploring the material properties of BDPs, including their composition, certified biodegradability, and performance, in applications such as mulching. In contrast, Cluster #0 reflects a shift in research focus from basic degradation processes to the ecological effects of the resulting fragments. Researchers such as Machado and Qi have led this transition. Previous studies have revealed that BDMPs are not harmless; they can affect the soil structure, microbial communities, and plant-microbe interactions. This work moves the conversation beyond biodegradable vs. nonbiodegradable plastics to a comprehensive understanding of the long-term environmental impacts of BDP residues in soils.

(2) Clusters #2 (mulching film) and #3 (soil-biodegradable plastic mulch). These clusters capture a move from concept to field validation. In foundational studies in Cluster #2, which established the early conceptual and methodological basis for later research, scholars identified mulching as a primary application, emphasizing its essential benefits, including water retention, weed control, and soil temperature regulation, often in comparison with conventional PE films. Cluster #3 involves examining materials engineered for soil degradation and their field performance. Prominent contributors such as Kasirajan and Sintim advanced this area with field experiments that featured testing real-

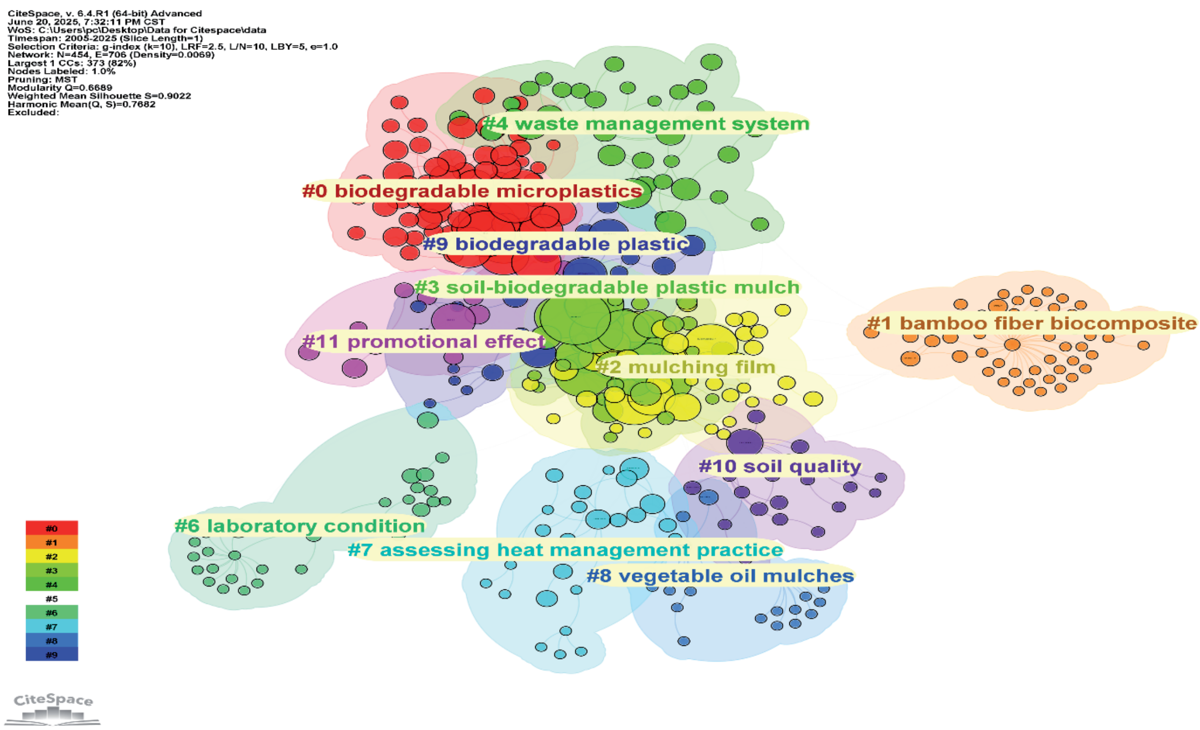

Fig. 6. Author co-citation network. Each node represents a cited author. Clusters of nodes indicate distinct research subdomains.

world breakdown rates under varying soils and climates. This line of work addresses the practical challenge of balancing agronomic function during the growing season with controlled post-use decomposition.

(3) Clusters #10 (soil quality) and #11 (promotional effect). These closely linked clusters shift the perspective from materials to agro-ecosystem outcomes [47]. Cluster #10 relies on a soil-centered perspective, measuring how BDP degradation products affect the physical structure, chemical properties, and biological health of soils. On this basis, Cluster #11 relies on a crop-centered view, quantifying effects on growth, nutrient uptake, and yield to connect soil improvements to productivity.

(4) Edge and specialized clusters. Other smaller clusters reflect emerging or specialized topics and add diversity to the field. For example, Cluster #1 (bamboo fiber biocomposite) investigates new BDP formulations using natural fillers; Clusters #6 (laboratory condition) and #7 (assessing heat management practices) denote specific experimental settings and evaluation criteria; and Cluster #8 (vegetable oil mulches) focuses on a particular biodegradable material type.

Reference Co-citation Network

Reference co-citation occurs when two or more publications are cited together in the references of a later study [48]. The established co-citation network, which exhibits very high modularity (Q = 0.8641) and high cohesion (S = 0.9339), is shown in Fig. 7. Each cluster is listed by influence (from highest to lowest) in Table 4. On the basis of their labels, spatial positions, and interconnections within the network, the clusters can be categorized into three primary research themes, which are interpreted as follows:

(1) Role and ecological effects of BDPs. This research theme reflects a distinct intellectual progression from materials science to ecosystem-level analysis [49]. As illustrated by representative literature, which in this study refers to works with high co-citation frequency and central positions within each cluster, the foundation of this progression is provided by Cluster #9 (BDPs), which outlines the core properties and conceptual debates surrounding BDPs and thus defines the scope of the research field. Building on this foundation [11], Cluster #6 (microbial communities) involves investigations of the primary degradation mechanisms, with a focus on the soil microorganisms that drive the breakdown process [50]. The ecological implications of these interactions are investigated at two distinct levels: Cluster #1 (soil ecosystem) provides a microscopic perspective, elucidating the formation of novel ecological niches and their substantial impacts on microbial activity at the soil–plastic interface [51]. These mechanistic insights culminate in the largest and most central cluster, Cluster #0 (soil-plant system), which integrates prior findings into a comprehensive assessment of the overall impact of BDPs on soil health in real-world agricultural systems [52].

(2) Application and practice in agricultural systems. This research theme emphasizes the transformation of BDP research results into tangible agricultural benefits. Cluster #2 (sustainable agricultural production systems)

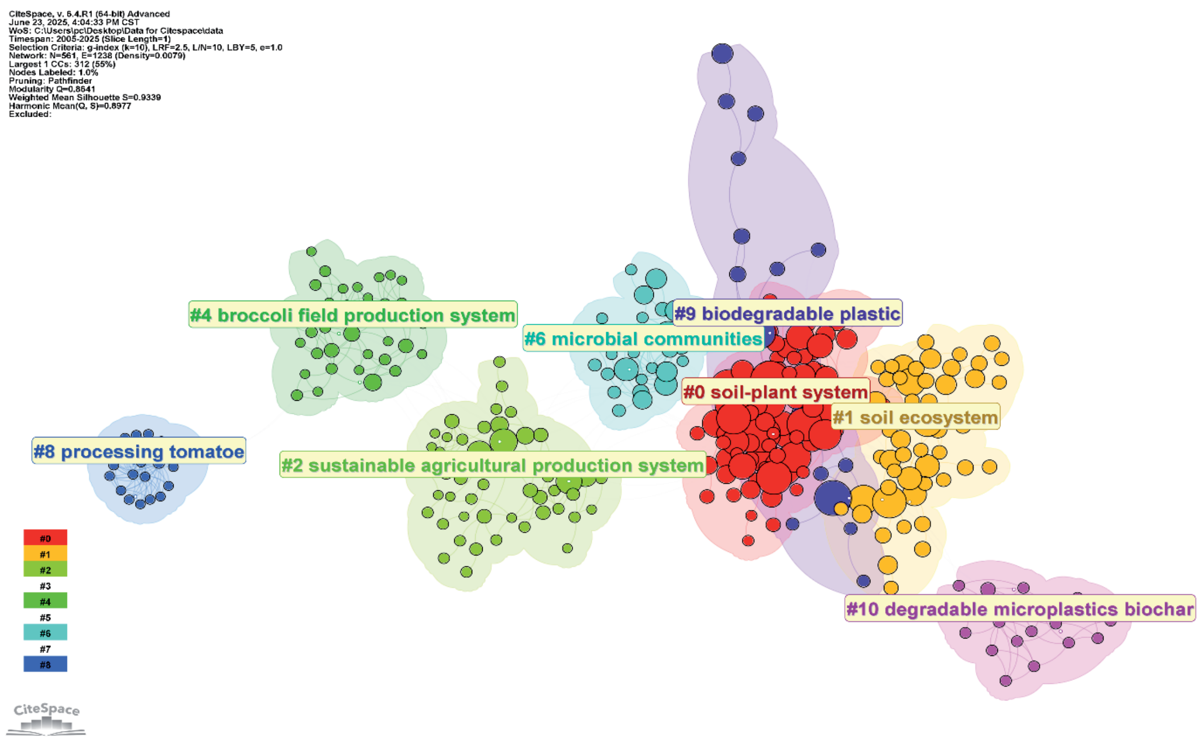

Fig. 7. Reference co-citation network. Each node represents a cited publication, and its clusters reflect different research themes.

Table 4. Details of each cluster listed in descending order of influence.

Cluster ID	Size	Silhouette	Mean (Year)	Label
0	90	0.946	2018	Soil-plant system
1	51	0.875	2020	Soil ecosystem
2	50	0.906	2012	Sustainable agricultural production system
4	34	0.986	2008	Broccoli field production system
6	28	0.899	2016	Microbial communities
8	20	0.978	2006	Processing tomatoes
9	17	0.961	2019	Biodegradable plastics
10	17	0.989	2022	Degradable microplastics biochar

involves comparing the limitations and advantages of traditional PE mulches and biodegradable mulches in agricultural production, thus laying the foundation for sustainable alternatives [41]. Studies in Cluster #4 (broccoli field production systems) [53] and Cluster #8 (processing tomatoes) [54] aim to explore specific field validations. The representative literature in Cluster #4 relies on broccoli as a test crop to evaluate the effects of weed control on various BDPs under specific agronomic conditions and their effects on crop yields. The representative literature in Cluster #8 relies on tomatoes as the test object. Through comparative field trials, the effects of different covering strategies on weed control, crop productivity, and even disease occurrence are evaluated, providing key real-world data for the practical application and challenges of BDPs in different agricultural environments.

(3) Emerging issues and environmental risks. The only cluster in this research theme is Cluster #10 (degradable microplastic biochar), the representative literature of which [55] indicates that after different types of BDMPs enter the soil, they induce soil organic carbon priming effects of different intensities and in different directions (namely, they accelerate or slow the decomposition of native soil organic matter). The intensity of this effect is closely related to the degradability of the microplastics themselves, which reveals the complex regulatory mechanism of BDMPs in the soil carbon cycle. This research theme reflects the scientific community's increasing understanding of BDPs, from focusing solely on degradable advantages to carefully evaluating new problems that may arise during degradation (such as BDMPs) and exploring innovative solutions (such as biochar technology).

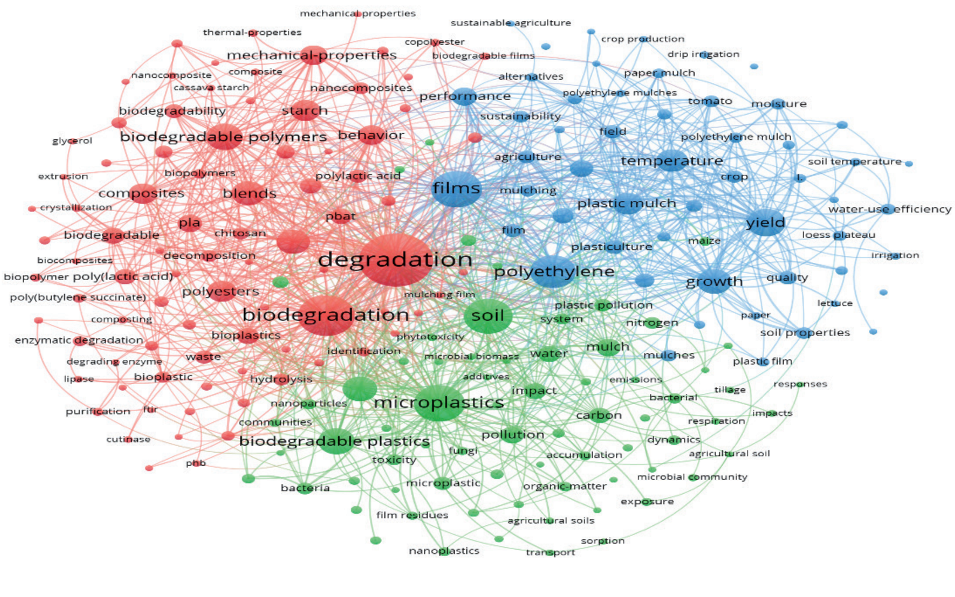

Fig. 8. Keyword cooccurrence network. The size of each node is proportional to its frequency of occurrence, clearly identifying the most dominant concepts, whereas the connecting lines indicate strong thematic links between keywords. The strategic positioning of certain keywords at cluster intersections highlights their role as conceptual bridges that integrate disparate research areas.

Keyword Analysis

Keyword Cooccurrence

Keywords provide a summary of an article and indicate its main content [56]. Analyzing keyword cooccurrence, which is defined as how often terms appear together in the literature, helps map the field and identify hotspots and structural relations [57]. The keyword cooccurrence network is shown in Fig. 8. A closer look points to three central pillars: materials science, agricultural application, and environmental behavior.

Cluster 1 (red) forms the materials science core of the domain. Key terms include “biodegradable polymers”, “PLA”, and “composites”, which indicate a focus on the development and characterization of BDPs. Related keywords such as “blends”, “mechanical properties”, “thermal properties”, and “crystallization” indicate a sustained study focus on engineering and optimizing materials for defined performance targets. This theme represents the upstream, technology-driven part of the field, where the goal is to create functional alternatives to conventional plastics.

Cluster 2 (blue) captures the practical dimension. Relevant studies account for BDPs in real agricultural systems. This research is anchored by the concept of “plastic mulch” and aims to examine whether BDPs can increase productivity. Terms such as “yield”, “growth”, “soil temperature”, and “water use efficiency” reflect the main agronomic outcomes under study. Crop names such as “maize” and “tomato” indicate a field-oriented, context-specific approach that checks performance under different growing conditions.

Cluster 3 (green) addresses what happens after the application of plastics. Central nodes include “microplastics”, “pollution”, and “soil”, which point to research on the environmental consequences of BDP use. The cooccurrence of “nanoparticles”, “toxicity”, “microbial community”, and “film residues” signals a more detailed and cautious evaluation of ecological risks from BDP degradation. The field has matured beyond a simple “biodegradable is good” view and now weighs potential long-term interactions with soils and biota.

In addition to detecting distinct thematic groups, the cooccurrence network reveals a consistent flow of knowledge, facilitated by particular “bridge” terms that link different research areas. Analyzing connection weights and nodal positions more closely shows that keywords such as “degradation” and “decomposition” serve as essential links between the Materials Science (Cluster 1) and the Agricultural Application (Cluster 2). This pattern suggests that the degradation behavior of materials is the key factor linking material design with agricultural performance; practical effectiveness is wholly determined by how well the designed breakdown timeline aligns with the stages of crop growth. Moreover, expressions such as “microplastics” and “film residues” act as central junctions tying Agricultural Application (Cluster 2) to Environmental Behavior (Cluster 3). This linkage demonstrates the sequential logic of research outcomes: agricultural mulching practices necessarily generate residual soil

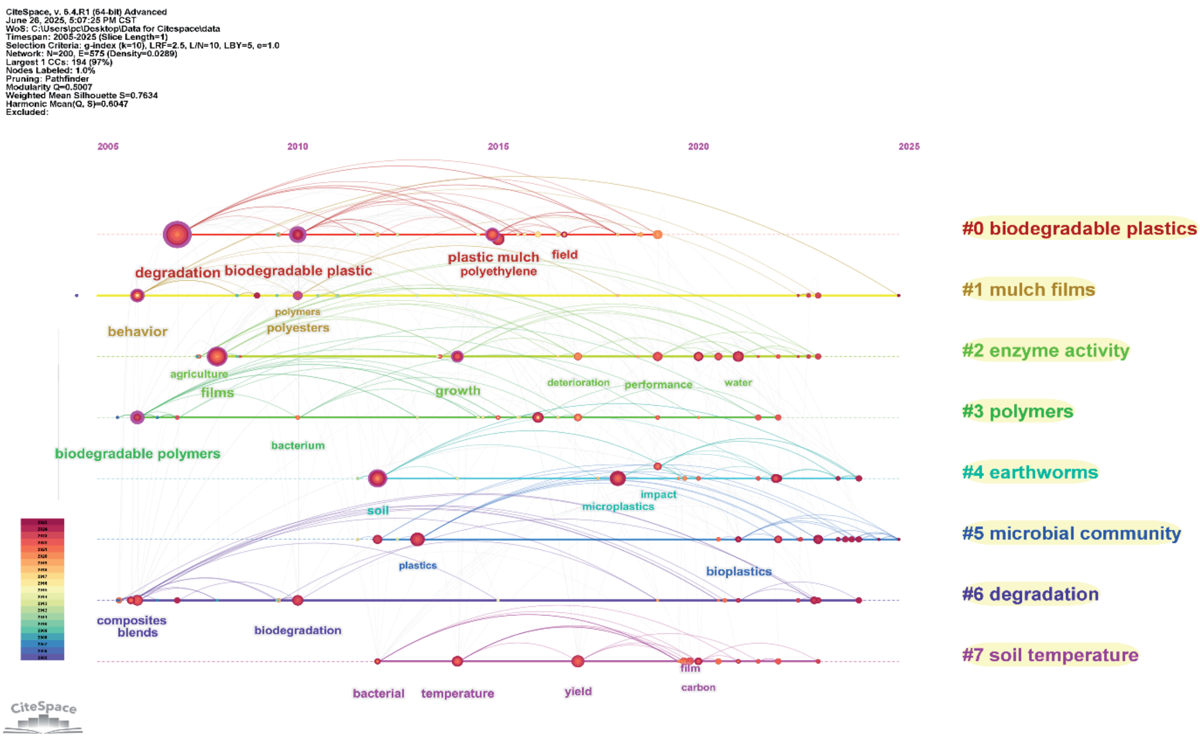

Fig. 9. Keyword timeline view.

contaminants, which then prompt the environmental risk analyses explored in Cluster 3. Together, these relationships outline the field's conceptual framework as a "Life Cycle Logic", tracing a path from material development through real-world testing and finally to ecological effect evaluation, indicating that the discipline has evolved into an integrated, cross-disciplinary research system.

Keyword Timeline View

The keyword timeline view is shown in Fig. 9, which shows a time-ordered map of cooccurring keywords arranged by year in this study; it provides a diachronic perspective on how research themes emerge, evolve, and shift over time [58]. We interpret the timeline from left to right [59] as follows:

The left side of the timeline is dominated by foundational clusters such as "#3 polymers", "#6 degradation", and "#7 soil temperature". During this early phase, researchers focused on materials science and examined the conceptual feasibility of BDPs and their initial agricultural potential.

Cluster #0 (BDPs) and Cluster #1 (mulch films) are located at the central stage of the timeline [60]. During this period, research moved from laboratory-based studies to field trials. BDPs were no longer discussed only in theory; studies compared them with PE films and validated their performance in practice. Cluster #4 (earthworms) signals a pivot toward biotic responses. As terms such as "soil", "impact", and "microplastics" became more frequent, researchers examined the environmental consequences of BDP degradation more systematically. These concerns began to shape how success was judged in studies.

On the right side of the timeline are the most recent directions [61]. Recent work narrows in scope but exhibits a more in-depth nature. Clusters #2 (enzyme activity) and #5 (microbial community) anchor this stage. Keywords such as "community", "enzyme activity", and "microbial degradation" point to a focus on the microbiology of breakdown. Cluster #4 extends into this period, and "plastic pollution" emerges as a key node at its endpoint. Overall, these shifts connect BDP research with the broader focus on plastic pollution governance.

Keyword Bursts

Keyword burst analysis aims to detect terms that sharply increase scholarly attention within a set time window and thus reveals emerging research areas [62]. The top ten keywords with the greatest citation bursts are listed in Table 5. The blue line indicates the whole timeline, the dark blue segment indicates when the term first appears, and the red segment indicates the burst period [63]. The beginning and end columns indicate the start and end years, respectively, of each burst. An analysis of these terms reveals a clear temporal evolution in research priorities:

(1) Preliminary exploration (2005-2016). During this period, keywords such as "biodegradable mulch" and "behavior" appeared frequently over a sustained span. This trend suggests that early investigations focused on applying BDPs as mulching films and assessing their broad performance and breakdown patterns.

(2) Transitional stage (2015-2021): This period was characterized by a rapid succession of bursts in field–related keywords, including "soil temperature", "degradation", "soil", "crop", and "water use efficiency". These emerging terms indicate a shift toward assessing the practical effects of BDPs on key agronomic variables.

(3) Current research frontier (2022-2024). Recent bursts of "plastics" and "PLA" show the field's current direction. The general term "plastics" signals closer links to the broader plastic pollution discourse. Moreover, the burst of "PLA" marks a move from broad discussion to material-specific studies on degradation mechanisms and environmental behaviors.

Table 5. Keyword burst table.

Keywords	Strength	Beginning	End	2005–2024
Biodegradable mulch	5.95	2005	2019	
Behavior	3.7	2006	2016	
Alternatives	4.42	2013	2019	
Soil temperature	3.19	2015	2021	
Deterioration	4.32	2017	2020	
Soil	3.98	2017	2020	
Crop	4.94	2019	2020	
Water use efficiency	3.16	2020	2021	
Plastics	3.42	2022	2024	
Pla	4.31	2023	2024	

(4) Overall, burst signals reveal how research priorities have evolved and delineate the current research frontier [64]. In this field, the progression follows a clear trajectory – from application-level topics to field performance and, subsequently, to environmental integration and material-specific mechanisms. “Plastics” and “PLA” emerge as key focal points for near-term study design.

Discussion

Principal Findings: A Three-Dimensional Research Structure

Our scientometric analysis revealed that the research on BDPs in soil is both diverse and uneven. This field of research is organized around a three-dimensional structure: materials science, agricultural applications, and environmental behavior. This tripartite framework reflects the material’s life cycle from synthesis to application and final disposal. To provide a deeper understanding, we summarize the status, methods, and challenges within each dimension below.

Materials Science

Research in this dimension focuses on polymer engineering and modification. The central objective in this domain is to develop PLA and PHA materials that match the mechanical performance of conventional PE while ensuring biodegradability [11]. Regarding methodological approaches, studies frequently employ analytical techniques like Fourier-transform infrared spectroscopy (FTIR) for structural analysis of polymers, complemented by respirometric assays to quantify mineralization rates in laboratory settings [65]. A significant challenge encountered is achieving an optimal compromise between the material’s necessary durability throughout its functional lifespan and its ability to decompose rapidly post-use. Frequently, formulated blends either undergo degradation too swiftly, compromising their effectiveness in applications such as mulching, or they remain in the environment as persistent debris, which poses difficulties for later soil management practices [66].

Agricultural Applications

This perspective redirects attention from the creation of materials to their functional application within agricultural systems. A consistent conclusion from multiple investigations is that biodegradable BDP mulch can successfully replicate the crop production advantages provided by PE films. These benefits include preserving soil water content, controlling weed growth, and enhancing yields for key crops such as maize and tomatoes [67]. Methodologically, research in this area depends extensively on comparative field trials that measure agricultural performance metrics. These metrics often encompass water-use efficiency, fluctuations in soil temperature, and overall crop output evaluated over several growing cycles. However, a significant obstacle persists despite these encouraging results: the inconsistent degradation behavior observed under actual field conditions. Field-based degradation, in contrast to the stability of laboratory settings, is substantially affected by fluctuating weather patterns and diverse soil compositions. This lack of environmental consistency can result in the mulch film fracturing too early while crops are growing, or failing to decompose fully after they are harvested, which subsequently presents practical management challenges for agricultural practitioners [13].

Environmental Behavior

This domain represents a critical evolution from simple degradation testing to complex ecological impact assessment. Recent research highlights that BDP degradation is a biologically driven process mediated by specific functional microbial taxa and extracellular enzymes, distinguishing it from the fragmentation of conventional plastics [68]. However, emerging evidence has raised concerns regarding the formation of BDMPs and their potential to alter soil physical properties and microbial community diversity. To investigate these complex interactions, researchers are increasingly adopting advanced molecular techniques, such as stable isotope probing and high-throughput sequencing, to trace microbial uptake of polymer-derived carbon. A major hurdle in this area is the lack of clarity regarding the long-term ecotoxicity of degradation byproducts and additives. Furthermore, accurately tracking the mineralization of BDPs in complex soil matrices remains methodologically difficult, limiting our ability to fully map the biogeochemical fate of these materials [69].

Intersections and Critical Gaps

While these three dimensions have evolved significantly, our analysis suggests they often operate in relative isolation, creating distinct knowledge gaps at their intersections. Materials scientists rarely test new polymer formulations in complex, living field soils, often missing how specific soil biota interact with novel chemical structures. Conversely, agronomic studies frequently focus on yield outcomes while overlooking the micro-scale ecological mechanisms driving material breakdown. A critical gap exists in understanding how material properties specifically dictate microbial colonization and how agronomic management practices interact with degradation rates. Future progress requires integrating these disparate perspectives to design materials that are agronomically robust yet ecologically benign.

Future Research Directions

Complex Interactions

Our analysis demonstrates that most scholars have examined the direct effects of BDPs in simplified or controlled soils. Although this work is valuable [70], the keyword cooccurrence network (Fig. 8) and the reference co-citation network (Fig. 7) show weak links between core BDP themes and terms for other common soil pollutants (e.g., heavy metals and pesticides) or soil amendments (e.g., biochar and organic fertilizer). This finding highlights a significant gap: interactive effects, both synergistic and antagonistic, have received little attention.

In real agricultural systems, soils are complex systems where BDPs do not exist in isolation [71]. To address this, future research must shift from simple toxicity tests to investigating the "vector effect" of BDP residues. Specifically, researchers need to determine whether the hydrophobic domains of degrading polymers (e.g., PBAT) concentrate organic pesticides or heavy metals, thereby altering their bioavailability. Methodologically, we propose using mesocosm experiments rather than sterile pot trials to simulate these interactions within realistic soil food webs. Furthermore, integrating transcriptomics and metabolomics will allow researchers to determine whether the combined presence of BDP microplastics and agrochemicals triggers synergistic stress responses in soil fauna (e.g., earthworms) distinct from single-stressor effects.

Intelligent and Functional Materials

Another direction is to shift BDPs from passive use to active functions. This includes designing "intelligent" or "functional" materials that provide more functions other than degrading after use. The core scientific challenge here lies in "synchronization": matching the polymer's hydrolysis rate with the crop's nutrient demand. For example, BDPs can be engineered via melt extrusion or electrospinning to encapsulate bio-stimulants or nano-fertilizers. Compared with conventional fertilizers, this strategy could increase nutrient use efficiency. However, achieving this requires the development of rigorous release kinetic models under varying soil moisture regimes. Future studies should focus on tailoring the polymer matrix structure so that degradation byproducts (e.g., oligomers) can serve as carbon sources for specific plant-growth-promoting rhizobacteria (PGPR), thereby actively building stable soil organic matter.

Socioeconomic Dimensions and Policy Integration

Although policy design and implementation have spurred research activity (Fig. 3), our review of publication outlets (Table 1) shows a significant gap: the socioeconomic dimensions of BDP adoption are understudied. The debate is currently dominated by natural sciences, isolating technological progress from practical uptake. To bridge this gap, future research should employ Life Cycle Costing (LCC) methodologies that explicitly monetize the "hidden costs" of conventional plastic pollution (e.g., soil yield decline and labor for removal). This would provide a fairer economic comparison than focusing solely on upfront material prices. Additionally, understanding farmer behavior requires more than anecdotal evidence; sociological studies using Choice Experiments (CE) and Willingness-to-Pay (WTP) analyses are needed to quantify specific barriers – such as skepticism regarding complete degradability that hinder widespread diffusion. By resolving these economic and behavioral questions, policymakers can design subsidy schemes that are empirically grounded and effective.

Limitations

This research exhibits several limitations that should be addressed. First, the scope of our data collection exclusively included publications indexed in the WoSCC [73]. Although the WoSCC is widely regarded as one of the best databases in the academic community, relevant literature in other databases (such as Scopus, Google Scholar, and region-specific literature databases) may have been overlooked. Second, non-English journals were excluded in the analysis. This decision was made to help ensure consistency throughout the research process. However, important non-English academic work has been overlooked, leading to an incomplete view of research from non-English-speaking regions. In future research, we can achieve a more comprehensive and global perspective by integrating multidatabase searches with multilingual analysis.

Conclusions

This research offers a comprehensive review of the current status, evolution, and future research directions of BDPs in soil environments on the basis of an analysis of publications from the WoSCC over the past two decades. Research has shown that the number of related publications in this field has increased significantly since 2019, and this growth trend is driven mainly by global policies aimed at reducing plastic pollution. Geographically, research in this area has been driven primarily by close collaboration between China and the United States, with European research centers providing valuable contributions. The knowledge structure of this field can be understood through a three-part narrative framework that spans the entire lifecycle of BDPs, namely, from materials science and agricultural applications to their environmental behaviors and long-term impacts in soil. Over time, the focus of research has shifted from an early optimistic attitude toward their performance to a more balanced understanding of potential ecological risks. Future research directions should move beyond isolated research models and delve deeper into the following areas: (1) how BDPs interact with other components in soil; (2) developing BDPs that not only degrade safely but also contribute positively to soil health; and (3) bridging technological innovation and real-world adoption by considering the social and economic factors influencing the application of BDPs.

Beyond this field, our results have broader implications for sustainable agriculture and the circular economy. This framework offers a practical template for evaluating other biobased materials and for linking material design, farm practices, and risk assessment. The documented shift from performance effects to ecosystem effects can inform standards, life cycle assessments, and product claims, and it can guide evidence-based regulation. The coupling between science and policy suggests that coordinated policy can speed up responsible deployment when it is paired with open data, shared protocols, and field trials. Pursuing these priorities will support the development of suitable metrics, better design choices, and safer, more effective use of BDPs in practice.

Data Availability Statement

The data in this paper are all from open-access platforms and are explained in the article; further inquiries can be directed to the corresponding author.

Acknowledgments

This work was funded by Qinghai Research and Design Institute of Environmental Sciences (Project Name: Screening of indigenous beneficial microbial communities for ecological restoration of degraded “Black Soil Beach” grasslands) and the Less Developed Regions of the National Natural Science Foundation of China (No. 32360283)

Conflict of Interest

The authors declare no conflict of interest.

References

1. MUHAMMADI, SHABINA, AFZAL M., HAMEED S. Bacterial polyhydroxyalkanoates-eco-friendly next generation plastic: production, biocompatibility, biodegradation, physical properties and applications. Green Chemistry Letters and Reviews, **8** (3-4), 56, **2015**.
2. BAMPS B., BUNTINX M., PEETERS R. Seal materials in flexible plastic food packaging: A review. Packaging Technology and Science, **36** (7), 507, **2023**.
3. GUO H., ZHOU X., LIU Z. Advanced Lightweight Structural Materials for Automobiles: Properties, Manipulation, and Perspective. Science of Advanced Materials, **16** (5), 563, **2024**.
4. KHAN S.B., IRFAN S., ZHANG Z., YUAN W. Redefining Medical Applications with Safe and Sustainable 3D Printing. ACS Applied Bio Materials, **2025**.
5. RHODES C.J. Solving the plastic problem: From cradle to grave, to reincarnation. Science Progress, **102** (3), 218, **2019**.
6. NKWACHUKWU O.I., CHIMA C.H., IKENNA A.O., ALBERT L. Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries. International Journal of Industrial Chemistry, **4**, 1, **2013**.
7. KUNWAR B., CHENG H., CHANDRASHEKARAN S.R., SHARMA B.K. Plastics to fuel: a review. Renewable and Sustainable Energy Reviews, **54**, 421, **2016**.
8. BRIASSOULIS D., PIKASI A., HISKAKIS M. End-of-waste life: Inventory of alternative end-of-use recirculation routes of bio-based plastics in the European Union context. Critical Reviews in Environmental Science and Technology, **49** (20), 1835, **2019**.
9. HUGGETT R. Soil as part of the Earth system. Progress in Physical Geography: Earth and Environment, **47** (3), 454, **2023**.
10. ZHOU Q., PAN C., WEI J.A., MA Z., LIU B., ZHANG D., WEI J., PAN X. Biodegradable plastics in soil: a significant gap from microplastics to nanoplastics and oligomers. Environmental Science: Nano, **12** (4), 2208, **2025**.
11. HAIDER T.P., VÖLKER C., KRAMM J., LANDFESTER K., WURM F.R. Plastics of the future? The impact of biodegradable polymers on the environment and on society. Angewandte Chemie International Edition, **58** (1), 50, **2019**.
12. ANDRADY A.L. Microplastics in the marine environment. Marine Pollution Bulletin, **62** (8), 1596, **2011**.
13. SANDER M. Biodegradation of polymeric mulch films in agricultural soils: concepts, knowledge gaps, and future research directions. Environmental Science & Technology, **53** (5), 2304, **2019**.
14. SINGH P., SHARMA V. Integrated plastic waste management: environmental and improved health approaches. Procedia Environmental Sciences, **35**, 692, **2016**.
15. CAO X., LIANG Y., JIANG J., MO A., HE D. Organic additives in agricultural plastics and their impacts on soil ecosystems: Compared with conventional and biodegradable plastics. TrAC Trends in Analytical Chemistry, **166,** 117212, **2023**.
16. UELAND Ø., GUNNLAUGSDOTTIR H., HOLM F., KALOGERAS N., LEINO O., LUTEIJN J., MAGNÚSSON S., ODEKERKEN G., POHJOLA M., TIJHUIS M. State of the art in benefit–risk analysis: Consumer perception. Food and Chemical Toxicology, **50** (1), 67, **2012**.
17. GREENHALGH T. Meta-narrative mapping: a new approach to the systematic review of complex evidence. Narrative Research in Health and Illness, 349, **2004**.
18. PRANCKUTĖ R. Web of Science (WoS) and Scopus: The titans of bibliographic information in today’s academic world. Publications, **9** (1), 12, **2021**.
19. WU J., YE X., CUI H. Recycled Materials in Construction: Trends, Status, and Future of Research. Sustainability, **17** (6), 2636, **2025**.
20. KEMEÇ A., ALTINAY A.T. Sustainable energy research trend: A bibliometric analysis using VOSviewer, RStudio

bibliometrix, and CiteSpace software tools. Sustainability, **15** (4), 3618, **2023**.
21. LOOSEN W., SCHMIDT J.-H. Multi-method approaches. The SAGE handbook of digital journalism, 562, **2016**.
22. IOANNIDIS J.P., BOYACK K.W., KLAVANS R. Estimates of the continuously publishing core in the scientific workforce. PloS One, **9** (7), e101698, **2014**.
23. RODRÍGUEZ-POSE A. Do institutions matter for regional development? Regional Studies, **47** (7), 1034, **2013**.
24. WANG X., CHENG Q., LU W. Analyzing evolution of research topics with NEViewer: a new method based on dynamic co-word networks. Scientometrics, **101**, 1253, **2014**.
25. GUEST G., MCLELLAN E. Distinguishing the trees from the forest: Applying cluster analysis to thematic qualitative data. Field Methods, **15** (2), 186, **2003**.
26. ARRUDA H., SILVA E.R., LESSA M., PROENÇA JR D., BARTHOLO R. VOSviewer and bibliometrix. Journal of the Medical Library Association: JMLA, **110** (3), 392, **2022**.
27. CHEN C., HU Z., LIU S., TSENG H. Emerging trends in regenerative medicine: a scientometric analysis in CiteSpace. Expert Opinion on Biological Therapy, **12** (5), 593, **2012**.
28. LONCAR M., BARRETT N.E., LIU G.-Z. Towards the refinement of forum and asynchronous online discussion in educational contexts worldwide: Trends and investigative approaches within a dominant research paradigm. Computers & Education, **73**, 93, **2014**.
29. ARAÚJO T., ABREU A., LOUÇÃ F. The evolution of Complexity co-occurring keywords: bibliometric analysis and network approach. Advances in Complex Systems, **27**, 4, **2024**.
30. LI Y., LI L., DENG W., ZHU D., HONG L. Building integrated photovoltaic (BIPV) development knowledge map: a review of visual analysis using CiteSpace. Buildings, **13** (2), 389, **2023**.
31. TU Y.N., HSU S.L. Constructing conceptual trajectory maps to trace the development of research fields. Journal of the Association for Information Science and Technology, **67** (8), 2016, **2016**.
32. GAGNON M.L. Moving knowledge to action through dissemination and exchange. Journal of Clinical Epidemiology, **64** (1), 25, **2011**.
33. WANG X., FENG X. Research on the relationships between discourse leading indicators and citations: perspectives from altmetrics indicators of international multidisciplinary academic journals. Library Hi Tech, **42** (4), 1165, **2024**.
34. ABRAMO G., D'ANGELO C.A. The relationship between the number of authors of a publication, its citations and the impact factor of the publishing journal: Evidence from Italy. Journal of Informetrics, **9** (4), 746, **2015**.
35. IQBAL A. Innovation speed and quality in higher education institutions: the role of knowledge management enablers and knowledge sharing process. Journal of Knowledge Management, **25** (9), 2334, **2021**.
36. ALBERTI F.G., BELFANTI F., GIUSTI J.D. Knowledge exchange and innovation in clusters: A dynamic social network analysis. Industry and Innovation, **28** (7), 880, **2021**.
37. ZHAO S., CACCIOLATTI L., LEE S.H., SONG W. Regional collaborations and indigenous innovation capabilities in China: A multivariate method for the analysis of regional innovation systems. Technological Forecasting and Social Change, **94**, 202, **2015**.
38. MORRISON A., RABELLOTTI R., ZIRULIA L. When do global pipelines enhance the diffusion of knowledge in clusters? Economic Geography, **89** (1), 77, **2013**.
39. RÅDBERG K. K., LÖFSTEN H. The entrepreneurial university and development of large-scale research infrastructure: Exploring the emerging university function of collaboration and leadership. The Journal of Technology Transfer, **49** (1), 334, **2024**.
40. KLEMINSKI R., KAZIENKO P., KAJDANOWICZ T. Analysis of direct citation, co-citation and bibliographic coupling in scientific topic identification. Journal of Information Science, **48** (3), 349, **2022**.
41. KASIRAJAN S., NGOUAJIO M. Polyethylene and biodegradable mulches for agricultural applications: a review. Agronomy for Sustainable Development, **32**, 501, **2012**.
42. SINTIM H.Y., BARY A.I., HAYES D.G., WADSWORTH L.C., ANUNCIADO M.B., ENGLISH M.E., BANDOPADHYAY S., SCHAEFFER S.M., DEBRUYN J.M., MILES C.A. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. Science of the total environment, **727**, 138668, **2020**.
43. HOFFMANN C.P., LUTZ C., MECKEL M. A relational altmetric? Network centrality on R esearch G ate as an indicator of scientific impact. Journal of the Association for Information Science and Technology, **67** (4), 765, **2016**.
44. STEINMETZ Z., WOLLMANN C., SCHAEFER M., BUCHMANN C., DAVID J., TRÖGER J., MUÑOZ K., FRÖR O., SCHAUMANN G.E. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Science of the Total Environment, **550**, 690, **2016**.
45. DE SOUZA MACHADO A.A., LAU C.W., KLOAS W., BERGMANN J., BACHELIER J.B., FALTIN E., BECKER R., GÖRLICH A.S., RILLIG M.C. Microplastics can change soil properties and affect plant performance. Environmental Science & Technology, **53** (10), 6044, **2019**.
46. QI Y., OSSOWICKI A., YANG X., LWANGA E.H., DINI-ANDREOTE F., GEISSEN V., GARBEVA P. Effects of plastic mulch film residues on wheat rhizosphere and soil properties. Journal of Hazardous Materials, **387**, 121711, **2020**.
47. ARABANI M., SHALCHIAN M.M., BAGHBANI A. A state-of-the-art review on interactive mechanisms and multi-scale application of biopolymers (BPs) in geo-improvement and vegetation growth. Journal of Environmental Management, **358**, 120905, **2024**.
48. BOYACK K.W., KLAVANS R. Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately? Journal of the American Society for information Science and Technology, **61** (12), 2389, **2010**.
49. SHI X., LIANG X., LUO Y. Unpacking the intellectual structure of ecosystem research in innovation studies. Research Policy, **52** (6), 104783, **2023**.
50. KADER M., SENGE M., MOJID M., ITO K. Recent advances in mulching materials and methods for modifying soil environment. Soil and Tillage Research, **168**, 155, **2017**.
51. ZHOU J., GUI H., BANFIELD C.C., WEN Y., ZANG H., DIPPOLD M.A., CHARLTON A., JONES D.L. The microplastisphere: Biodegradable microplastics addition alters soil microbial community structure and function. Soil Biology and Biochemistry, **156**, 108211, **2021**.
52. SINTIM H.Y., BANDOPADHYAY S., ENGLISH M.E., BARY A.I., DEBRUYN J.M., SCHAEFFER S.M.,

MILES C.A., REGANOLD J.P., FLURY M. Impacts of biodegradable plastic mulches on soil health. Agriculture, Ecosystems & Environment, **273**, 36, **2019**.
53. ANZALONE A., CIRUJEDA A., AIBAR J., PARDO G., ZARAGOZA C. Effect of biodegradable mulch materials on weed control in processing tomatoes. Weed Technology, **24** (3), 369, **2010**.
54. SERRANO-RUIZ H., MARTIN-CLOSAS L., PELACHO A.M. Impact of buried debris from agricultural biodegradable plastic mulches on two horticultural crop plants: Tomato and lettuce. Science of the Total Environment, **856**, 159167, **2023**.
55. ZHANG G., LIU D., LIN J., KUMAR A., JIA K., TIAN X., YU Z., ZHU B. Priming effects induced by degradable microplastics in agricultural soils. Soil Biology and Biochemistry, **180**, 109006, **2023**.
56. TANG X., ZENG Q. Keyword clustering for user interest profiling refinement within paper recommender systems. Journal of Systems and Software, **85** (1), 87, **2012**.
57. SEDIGHI M. Application of word co-occurrence analysis method in mapping of the scientific fields (case study: the field of Informetrics). Library Review, **65** (1/2), 52, **2016**.
58. WIDDERSHEIM M.M. Historical case study: A research strategy for diachronic analysis. Library & Information Science Research, **40** (2), 144, **2018**.
59. ULRICH R., MAIENBORN C. Left–right coding of past and future in language: The mental timeline during sentence processing. Cognition, **117** (2), 126, **2010**.
60. ARIAS N., MÉNDEZ M., VALLEJO G., ARIAS J.L. Finding the place without the whole: Timeline involvement of brain regions. Brain Research, **1625**, 18, **2015**.
61. STREET C.T., WARD K.W. Improving validity and reliability in longitudinal case study timelines. European journal of Information Systems, **21** (2), 160, **2012**.
62. TATTERSHALL E., NENADIC G., STEVENS R.D. Detecting bursty terms in computer science research. Scientometrics, **122** (1), 681, **2020**.
63. GENG Y., JIANG X., BAI W., YAN Y., GAO J. Research progress of tourism marketing over 30 years: Bibliometrics based on CiteSpace. Ecological Indicators, **162**, 112059, **2024**.
64. WANG S., LV X. Hot topics and evolution of frontier research in early education: A bibliometric mapping of the research literature (2001-2020). Sustainability, **13** (16), 9216, **2021**.
65. NARANCIC T., VERSTICHEL S., REDDY CHAGANTI S., MORALES-GAMEZ L., KENNY S.T., DE WILDE B., BABU PADAMATI R., O'CONNOR K.E. Biodegradable plastic blends create new possibilities for end-of-life management of plastics but they are not a panacea for plastic pollution. Environmental Science & Technology, **52** (18), 10441, **2018**.
66. LAYCOCK B., NIKOLIĆ M., COLWELL J.M., GAUTHIER E., HALLEY P., BOTTLE S., GEORGE G. Lifetime prediction of biodegradable polymers. Progress in Polymer Science, **71**, 144, **2017**.
67. KASIRAJAN S., NGOUAJIO M. Polyethylene and biodegradable mulches for agricultural applications: a review. Agronomy for Sustainable Development, **32** (2), 501, **2012**.
68. ZUMSTEIN M.T., SCHINTLMEISTER A., NELSON T.F., BAUMGARTNER R., WOEBKEN D., WAGNER M., KOHLER H.-P.E., MCNEILL K., SANDER M. Biodegradation of synthetic polymers in soils: Tracking carbon into CO_2 and microbial biomass. Science Advances, **4** (7), eaas9024, **2018**.
69. LI M. A novel three-dimension perspective to explore technology evolution. Scientometrics, **105** (3), 1679, **2015**.
70. PETIT J.-C. Why do we need fundamental research? European Review, **12** (2), 191, **2004**.
71. CREAMER R., BAREL J., BONGIORNO G., ZWETSLOOT M. The life of soils: Integrating the who and how of multifunctionality. Soil Biology and Biochemistry, **166**, 108561, **2022**.
72. EHIGIAMUSOE K.U., DOGAN E. The role of interaction effect between renewable energy consumption and real income in carbon emissions: evidence from low-income countries. Renewable and Sustainable Energy Reviews, **154**, 111883, **2022**.
73. CROSTHWAITE P., NINGRUM S., LEE I. Research trends in L2 written corrective feedback: A bibliometric analysis of three decades of Scopus-indexed research on L2 WCF. Journal of Second Language Writing, **58**, 100934, **2022**.