Applied Environmental Biotechnology

Review article

Micro- and nanoplastics in biological wastewater and sludge treatment: A bibliometric and critical review of fate, removal, process interactions, and research gaps (2015–2026)

Tirmizhi Munkaila Abubakar[1,2], Oloche Job Ibrahim[1], Mustapha Abba[2,3], Abdullahi Adamu Faggo[3], Bashar Haruna Gulumbe[4], Abdussamad Abubakar[2], Nurulfiza Mat Isa[5] and Nor Azimah Mohd Zain[1]*

[1]Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia

[2]Department of Biotechnology, Faculty of Science, Federal University of Health Sciences, Azare, Bauchi State, Nigeria

[3]Department of Microbiology, Faculty of Science, Sa'adu Zungur University, Gadau, Bauchi State, Nigeria

[4]Department of Microbiology, Faculty of Science, Federal University Birnin Kebbi, Birnin Kebbi, Kebbi State, Nigeria

[5]Department of Cell and Molecular Biology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, Serdang, Selangor, Malaysia

***Corresponding author:**
Nor Azimah Mohd Zain
(norazimah@utm.my)

Citation: Abubakar, T. M., Ibrahim, O. J., Abba, M., Faggo, A. A., Gulumbe, B. H., Abubakar, A., Isa, M. N., & Zain, N. A. M. Micro- and nanoplastics in biological wastewater and sludge treatment: A bibliometric and critical review of fate, removal, process interactions, and research gaps (2015–2026). *Appl Environ Biotechnol*. http://doi.org/10.26789/AEB.2026.01.007

Received: November 18, 2026

Revised: November 21, 2026

Accepted: November 25, 2026

Published online: November 25 2026

Copyright: © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.

Publisher's Note: AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract

Wastewater treatment plants intercept most microplastics in sewage, and their biological stages and sludge line determine where these particles end up and how they affect the microbial processes on which treatment depends. This study combined bibliometric analysis with a critical review of micro- and nanoplastic research in biological wastewater and sludge treatment. A Scopus search returned 1,536 records, and 645 articles (2015–2026) were analysed with bibliometrix and VOSviewer. Output rose from one article in 2015 to 133 in 2025 (Mann–Kendall $Z = 3.83$, $p < 0.001$; Sen's slope 13.50 articles per year). China accounted for 51.9% of articles by corresponding author, whereas only seven articles involved an African institution. *Journal of Hazardous Materials*, *Water Research*, *Science of the Total Environment*, and *Chemical Engineering Journal* formed the Bradford core. Keyword co-occurrence analysis resolved four clusters: occurrence, fate, and removal in wastewater treatment plants; membrane and biofilm systems and biodegradable microplastics; anaerobic digestion, extracellular polymeric substances, and the resistome; and nanoplastic effects on nitrogen transformation. Anaerobic digestion, sewage sludge, and antibiotic resistance genes formed the only motor theme. Conventional plants achieve high retention mainly by transferring particles to sludge, which digestion does not clear of conventional polymers. Effects on nitrification, denitrification, and methanogenesis depend on polymer type, particle size, dose, and additive leaching, and several arise only at concentrations above those measured in practice. Priorities include harmonised analytical methods, measurement of nanoplastics in real matrices, realistic exposure experiments, full-scale sludge-line mass balances, and research capacity in under-represented regions.

Keywords: Microplastics; Nanoplastics; Activated sludge; Anaerobic digestion; Antibiotic resistance genes; Bibliometric analysis

1. Introduction

Municipal sewage carries microplastics from the washing of synthetic textiles, personal care products, and polymer manufacturing, and wastewater treatment plants (WWTPs) are the first engineered barrier nano-/microparticles meet before reaching surface waters (Liu *et al.*, 2019; Ziajahromi *et al.*, 2021). Field studies published in the late 2010s showed that plants with secondary treatment retain most of the incoming load. A Finnish activated sludge plant retained 98.3% of microplastics (Lares *et al.*, 2018), and a tertiary plant serving about 800,000 population equivalents retained more than 99% of microlitter once secondary treatment was complete (Talvitie, Mikola, Setälä, *et al.*, 2017). Retention on this scale does not make effluent negligible. An Italian plant that removed 84% of incoming microplastics was still estimated to release about 160 million particles/day because of the volume it discharges (Magni *et al.*, 2019).

High retention also means that the particles are moved rather than destroyed. Mass balances show that most of the retained load ends up in screenings and sludge. At three Australian plants, screening and grit removal captured 69%–79% of influent microplastics, 8%–16% ended in biosolids, and only 0.2%–1.8% left with the final effluent (Ziajahromi *et al.*, 2021). At a Finnish plant, about 80% of the microlitter removed from the water line was found in dried sludge, and the remainder was returned to the process with reject water (Talvitie, Mikola, Setälä, *et al.*, 2017). Sludge from one United Kingdom (UK) works contained 37.7–286.5 microplastics/g dry weight (dw), and the authors noted that about 3.5 million tonnes (wet weight) of biosolids are recycled to UK farmland each year (Harley-Nyang *et al.*, 2022). Once applied to soil, fibres are strongly retained in the surface layer, whereas nanoplastics can be transported with the mobile organic fraction (Keller *et al.*, 2020). The sludge line therefore determines whether treatment-captured microplastics re-enter the environment.

Biological treatment units are not passive sinks. Microplastics and nanoplastics come into direct contact with flocs, biofilms, granules, and digester communities, and a growing number of studies report effects on the processes those communities perform. Polyvinyl chloride (PVC) and polyethylene (PE) microplastics reduced methane production from waste activated sludge through bisphenol A leaching and oxidative stress, respectively (Wei, Huang, Sun, Dai, & Ni, 2019; Wei, Huang, Sun, Wang, *et al.*, 2019). Polystyrene (PS) nanoplastics reduced total nitrogen removal in constructed wetlands by 29.5%–40.6% (Yang *et al.*, 2020), and particle surfaces in activated sludge and digesters selectively enriched antibiotic resistance genes (ARGs) and their hosts (Luo, Dai, Wei, *et al.*, 2023; Pham *et al.*, 2021). These findings link microplastic research to process stability, sludge valorisation, and the spread of antimicrobial resistance, all of which are central concerns of environmental biotechnology.

Several reviews have covered parts of this subject. Rout *et al.* (2022) and Ahmed *et al.* (2024) summarised removal mechanisms and management options in WWTPs; Liu *et al.* (2022) and X. Wu *et al.* (2022) examined how treatment ages and fragments microplastics; and Zhou *et al.* (2024) reviewed toxic effects on microorganisms in biological treatment units. Bibliometric studies have mapped microplastic research in wastewater as a whole (Alazaiza *et al.*, 2025) and in soils amended with sewage sludge (B. Fu *et al.*, 2024). To our knowledge, none has combined a screened corpus restricted to biological wastewater and sludge treatment with a critical evaluation of removal, fate, and process interactions. Keyword maps describe the structure of a literature rather than the strength of its evidence (Aria & Cuccurullo, 2017; Van Eck & Waltman, 2010), so a bibliometric analysis read together with the underlying studies is more useful than either approach alone.

Building on these gaps, this study examines the development of research on micro- and nanoplastics in biological wastewater and sludge treatment between 2015 and 2026. It analyses publication growth and the contributions of leading journals, authors, institutions, and countries, while exploring the conceptual structure of the field and identifying established and emerging research themes. Beyond mapping research trends, the study critically evaluates evidence on removal performance, the fate of micro- and nanoplastics in the sludge line, their retention and transformation mechanisms, and their interactions with biological treatment processes. It further identifies limitations in the existing evidence and highlights research priorities to guide future investigations and improve understanding of the behaviour and management of micro- and nanoplastics in biological wastewater and sludge treatment systems.

2. Methods

2.1. Data source and search strategy

Scopus was searched on November 13, 2026 using the following query in the title, abstract, and keyword fields: TITLE-ABS-KEY ([microplastic* OR "micro-plastic*" OR nanoplastic* OR "nano-plastic*" OR "microfiber*" OR "microfibre*" OR microbead* OR "plastic particle*" OR "plastic nanoparticle*" OR "polystyrene nanoparticle*" OR "polystyrene microsphere*"] AND [wastewater* OR sewage OR effluent* OR sludge OR "wastewater treatment

plant*" OR WWTP* OR "sewage treatment plant*" OR "municipal wastewater"] AND ["activated sludge" OR "membrane bioreactor*" OR "biological wastewater treatment" OR "biological treatment" OR "secondary treatment" OR "biofilm reactor*" OR "moving bed biofilm" OR "trickling filter*" OR "aerobic granular sludge" OR "sequencing batch reactor*" OR "anaerobic digestion" OR UASB OR "constructed wetland*" OR "microalgae-bacteria" OR "algal-bacterial" OR "microbial degradation" OR biodegrad*]). Nanoplastic terms were extended to PS nanoparticles and microspheres because much of the work on nanoplastic effects in sludge uses these descriptors rather than the word "nanoplastic." The search returned 1,536 records. Records published outside 2003–2026 (n = 12), document types other than research articles (n = 554), and non-English publications (n = 34) were removed, and the remaining 936 records were exported with full bibliographic information and cited references. The search window opened in 2003, but the earliest eligible article was published in 2015, so the analysis covers 2015–2026. Because 2026 was incomplete at the time of export, articles from that year were included in descriptive analyses but excluded from trend testing.

2.2. Screening and eligibility

Records were eligible if they reported primary research on micro- or nanoplastics in a biological wastewater treatment process or in the treatment of sewage sludge. Eligible settings included activated sludge, membrane bioreactors (MBRs), biofilm and granular sludge systems, constructed wetlands, anaerobic digestion, and composting or vermicomposting of sludge. Eligible endpoints included occurrence and removal, fate and transformation, biodegradation, and effects on process performance, microbial communities, or resistance genes. Two exclusion criteria were applied. The first exclusion criterion removed reviews, bibliometric analyses, and meta-analyses indexed by Scopus as articles (n = 93). The second criterion removed records without a biological wastewater or sludge treatment context (n = 198), such as studies of soils and crops, marine and freshwater environments, physicochemical or thermal treatment only, analytical methods only, and plastic sources such as textile washing. Records were first flagged by searching titles, abstracts, and keywords for treatment-process terms, and flagged records were then read and judged individually; where eligibility remained unclear, the full text was consulted. Screening was carried out independently by two authors (TMA and OJI), and disagreements were resolved by discussion. The final dataset comprised 645 articles. The selection process is summarised in Figure 1 following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page *et al.*, 2021).

2.3. Data cleaning and harmonisation

No duplicate records were identified by DOI, title, or Scopus EID. One journal title that appeared twice because of a trailing space was merged, giving 136 sources rather than the 137 reported by bibliometrix. Name-based author counting groups different researchers who share a surname and initial, a problem that is acute for common Chinese surnames, so authors were disambiguated using Scopus Author IDs. Institutions were counted once per article and harmonised at university level from the Scopus affiliation field. Author keywords were standardised with a thesaurus of more than 130 synonym groups that merged spelling variants, plurals, and abbreviations (for example, WWTP, wastewater treatment plants, and sewage treatment plants), and generic terms such as "pollution" and "characteristics" were excluded.

2.4. Bibliometric and statistical analysis

Performance indicators, source, author statistics, and the thematic map were produced with the bibliometrix R package through its Biblioshiny interface (Aria & Cuccurullo, 2017). The trend in annual output for the full years 2015–2025 was tested with the Mann–Kendall test, and its magnitude was estimated with Sen's slope (Kendall, 1975; Mann, 1945; Sen, 1968). Core journals were identified by dividing sources into three zones of approximately equal article counts (Bradford, 1985). Author productivity was compared with Lotka's inverse-square law and the fit assessed with a Kolmogorov–Smirnov test (Lotka, 1926; Pao, 1985). Local h-indices were calculated from citations to articles within the dataset.

Keyword co-occurrence was analysed in VOSviewer (Van Eck & Waltman, 2010) using author keywords, full counting, association-strength normalisation, and a minimum of eight occurrences, retaining 58 of 1,375 keywords. Average publication year was used to distinguish established from recent themes. The conceptual structure was examined with a thematic map built from 250 author keywords and Walktrap clustering, in which themes are positioned by Callon centrality and density (Callon *et al.*, 1991; Cobo *et al.*, 2011). The search term (microplastics) and generic terms were removed before the thematic map was built so that the themes reflected substantive topics.

2.5. Critical review

The critical review drew on the included articles and was organised around the themes identified by the co-occurrence and thematic analyses. Quantitative values quoted in the review were taken from the original studies, and the experimental conditions under which they were obtained (scale, polymer, particle size, and exposure concentration) were considered when comparing results.

3. Results

3.1. Overview of the dataset

The final dataset comprised 645 research articles published in 136 sources between 2015 and 2026 (Table 1). The articles cited 69,293 references and had a mean of 48.68 citations each, but the median was only 18, and the 10 most cited articles accounted for 24.1% of all citations. The field is therefore young (mean document age 2.36 years) and its citation impact is concentrated in a small group of early studies. Collaboration was the norm: only two articles had a single author, the mean number of co-authors was 6.12, and 23.88% of articles involved international co-authorship. bibliometrix reported 2,133 authors using name matching; disambiguation by Scopus Author ID identified 2,972 distinct authors, and the latter figure is used in Section 3.4.

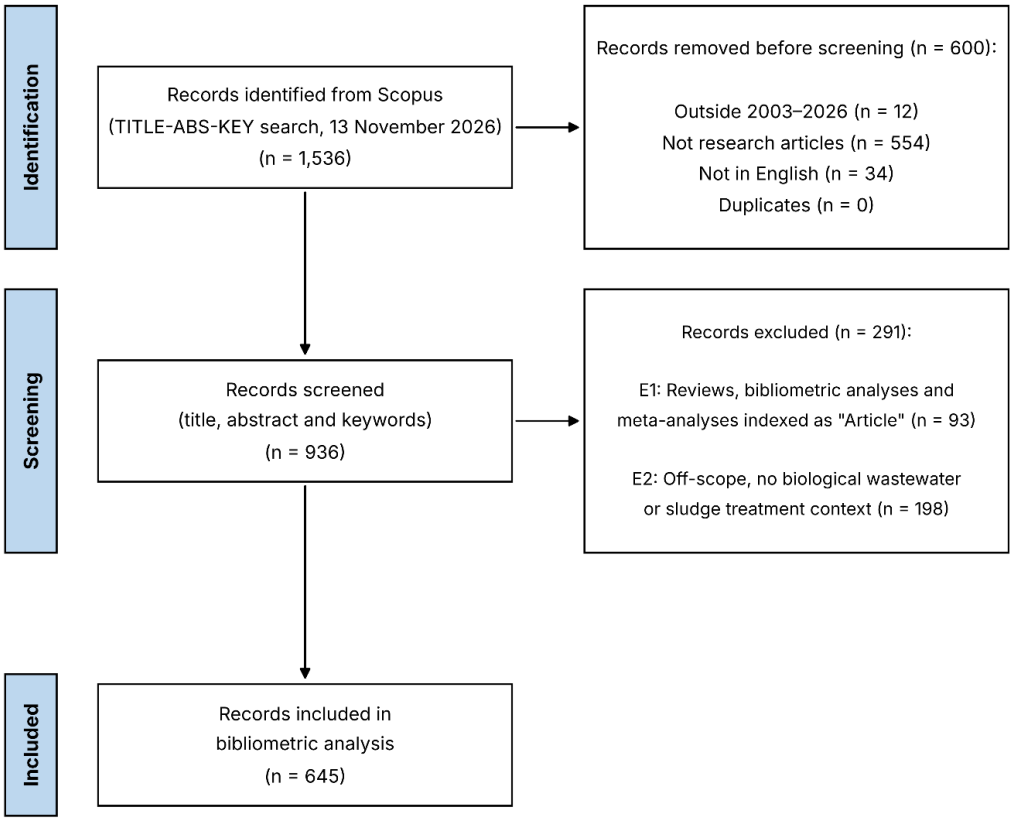

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 flow diagram of record identification, screening, and inclusion

3.2. Annual scientific production and citation trends

Annual output increased from 1 article in 2015 to 133 in 2025, with 134 articles already indexed for 2026 at the time of the search (Figure 2). Output rose most sharply between 2021 and 2022, from 35 to 89 articles, fell to 77 in 2023 and then resumed its growth. Articles published from 2022 onwards account for 85.9% of the dataset. The Mann–Kendall test confirmed a significant monotonic increase over 2015–2025 ($Z = 3.83$, Kendall's $\tau = 0.917$, $p < 0.001$), with a Sen's slope of 13.50 additional articles per year. The compound annual growth rate of 56.09% reported by bibliometrix is inflated by the single-article base year and the incomplete final year and is not used for interpretation.

Table 1. Main information on the dataset of micro- and nanoplastics in biological wastewater and sludge treatment research (2015–2026)

Description	Results
Main data information	
Timespan	2015–2026
Sources (journals)	136
Documents (research articles)	645
Annual growth rate, 2015–2026 (%)	56.09
Document average age (years)	2.36
Average citations per document	48.68
Median citations per document	18
References	69,293
Document contents	
Keywords Plus (ID)	5,608
Author's keywords (DE)	1,597
Authors	
Authors	2,133/2972
Authors of single-authored documents	2
Authors collaboration	
Single-authored documents	2
Co-authors per document	6.12
International co-authorships (%)	23.88
Publication trend, 2015–2025	
Mann–Kendall Z	3.83
Kendall's τ	0.917
p-value	<0.001
Sen's slope (articles/year)	13.50

Notes: The annual growth rate was computed by bibliometrix from 1 article (2015) to 134 articles (2026); because 2026 is incomplete (search date November 13, 2026) and the base year contains a single article, this rate is inflated and should be interpreted with caution. The number of sources (136) differs from the bibliometrix value (137) because one journal title appeared twice in Scopus owing to a trailing space and was merged. Name-based author matching yielded 2,133 authors, whereas Scopus Author ID disambiguation yielded 2,972 distinct authors. Median citations were calculated from the Scopus "Cited by" field of the final dataset (n = 645). The Mann–Kendall trend test and Sen's slope estimator were applied to annual article counts for the complete years 2015–2025.

Mean total citations per year peaked for articles published in 2017 (61.45) and declined steadily for later publication years (Figure 3). The peak reflects the early full-scale studies of removal in Finnish and other European plants (Mahon *et al.*, 2017; Talvitie, Mikola, Koistinen, Setälä, 2017; Talvitie, Mikola, Setälä, *et al.*, 2017), which remain the reference points for later work. The decline in recent years is expected, because newer articles have had less time to accumulate citations.

3.3. Most relevant and influential sources

The 10 most relevant sources published 382 articles, representing 59.22% of the dataset (Table 2). *Journal of Hazardous Materials* published the most articles (75), followed by *Water Research* (56) and *Science of the Total Environment* (55). *Water Research* had the greatest influence, with 7,327 citations, 130.84 citations per article, and a local *h*-index of 35, reflecting its role in publishing the early full-scale removal studies. *Chemosphere* combined a moderate article count with high citations per article (92.79). *Bioresource Technology* and *Journal of Environmental Chemical Engineering* published their first articles on the topic only in 2022, matching the later shift towards sludge processing and treatment technology.

Bradford's law placed four journals in the core zone (*Journal of Hazardous Materials*, *Water Research*, *Science of the Total Environment*, and *Chemical Engineering Journal*), which together published 221 articles (34.26%). Zone 2 contained 11 journals and 216 articles, and Zone 3 contained 121 journals and 208 articles (Figure 4). The ratio of sources across zones (1:2.75:30.25) departs from the geometric progression predicted by Bradford, because Zone 3 is much larger than expected. A small core of environmental journals carries a third of the literature, while the remainder is spread thinly across many journals, many of which published only one or two articles on the subject.

3.4. Authors and productivity

Eleven authors published at least eight articles (Table 3). Bing-Jie Ni (19 articles, 2,231 citations, *h*-index 17) and Wei Wei (12 articles, 1,893 citations, *h*-index 12), both at the University of Technology Sydney, were the most productive and among the most cited, largely through their work on microplastic effects on anaerobic digestion of waste activated sludge and on resistance genes in digesters. Xiaohu Dai (Tongji University) followed with 10 articles, as did J.A. Mendoza-Roca and M.A. Bes-Piá (Universitat Politècnica de València), whose work covers the separation of microplastics from sludge and their effects on activated sludge and anaerobic digestion. Figure 5 shows that the Sydney and Tongji groups were active from 2019, the groups at the Institute of Hydrobiology (Chinese Academy of Sciences) published mainly in 2020–2022, and the groups at the University of Alberta and the University of Warmia and Mazury entered the field in 2022.

Author productivity was highly skewed. Of the 2,972 disambiguated authors, 79.14% contributed a single article

and only 39 contributed five or more. The log–log regression of the productivity distribution gave an exponent β of 3.04 (R^2 = 0.91), much steeper than the value of 2 expected under Lotka's law, and the Kolmogorov–Smirnov test rejected Lotka's law (Dmax = 0.164; critical value at α = 0.01 is 0.030). The pattern is typical of a young, fast-growing field that many researchers enter from neighbouring topics such as wastewater engineering, sludge treatment, and antimicrobial resistance, while relatively few have built sustained research programmes on it.

Table 2. Top 10 most relevant sources publishing research on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Rank	Source	Articles	%	TC	TC/article	*h*-index	First year
1	*Journal of Hazardous Materials*	75	11.63	2,674	35.65	29	2020
2	*Water Research*	56	8.68	7,327	130.84	35	2017
3	*Science of the Total Environment*	55	8.53	3,372	61.31	31	2018
4	*Chemical Engineering Journal*	35	5.43	2,033	58.09	19	2019
4	*Journal of Environmental Management*	35	5.43	750	21.43	14	2020
6	*Environmental Pollution*	31	4.81	1,588	51.23	20	2018
7	*Bioresource Technology*	26	4.03	629	24.19	15	2022
8	*Chemosphere*	24	3.72	2,227	92.79	20	2017
8	*Journal of Environmental Chemical Engineering*	24	3.72	460	19.17	10	2022
10	*Journal of Water Process Engineering*	21	3.26	295	14.05	7	2020

Notes: % = Share of the 645 articles; TC = Total citations (Scopus "Cited by", search date November 13, 2026); *h*-index = Local *h*-index calculated from the citations of articles in the dataset; First year = Year of the first article on the topic published in the source. The top 10 sources together published 382 articles (59.22% of the dataset). Article counts are from Biblioshiny (bibliometrix) Most Relevant Sources output.

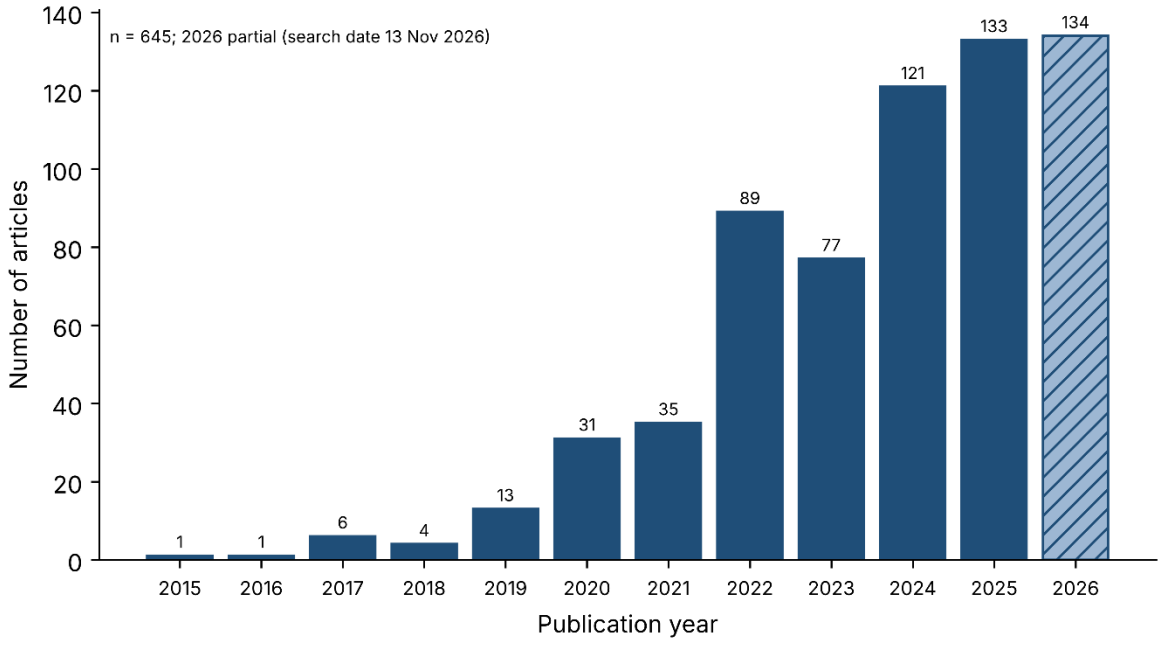

Figure 2. Annual number of research articles on micro- and nanoplastics in biological wastewater and sludge treatment, 2015–2026 (n = 645). The hatched bar denotes the incomplete 2026 count (search date November 13, 2026).

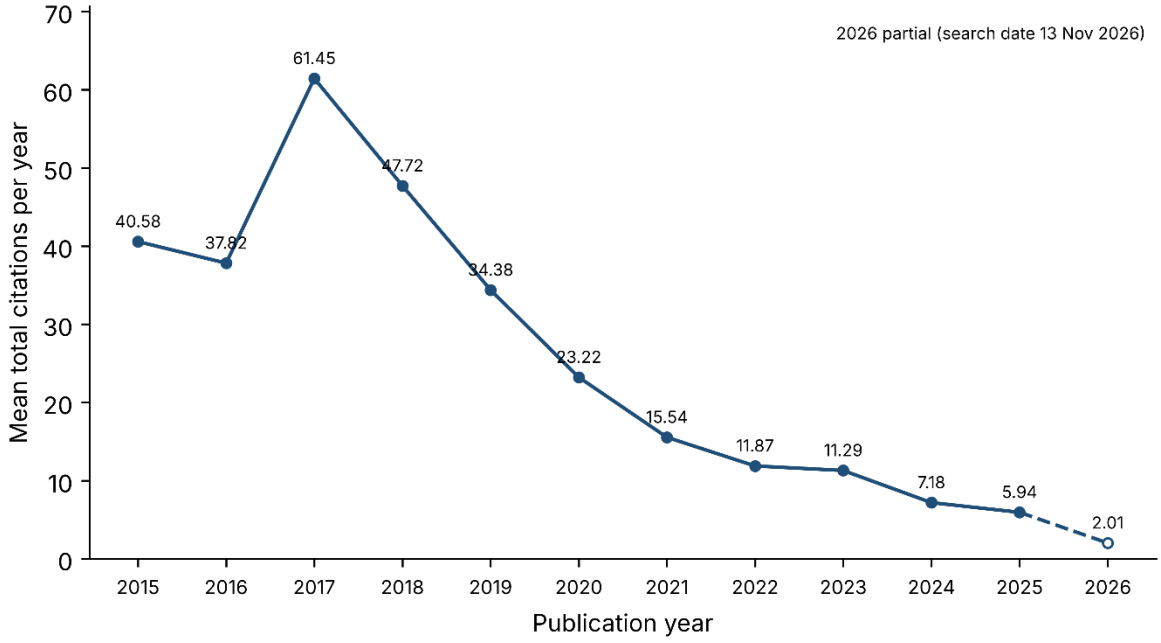

Figure 3. Mean total citations per year by publication year, 2015–2026. The dashed segment and open marker denote the incomplete 2026 count.

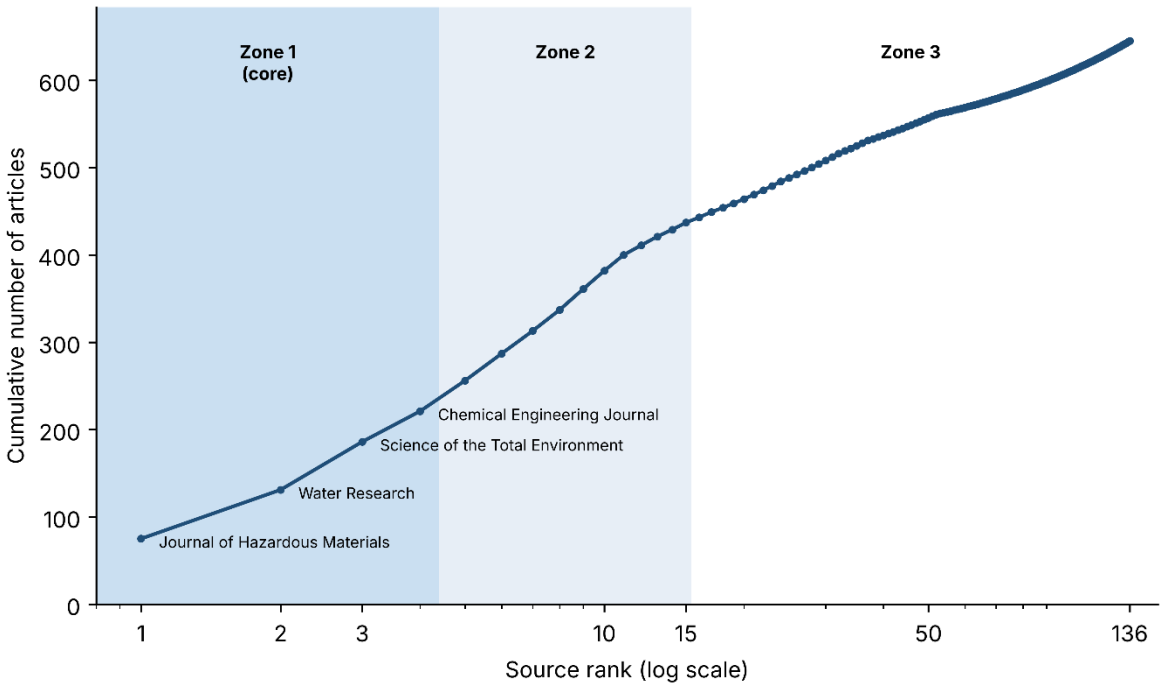

Figure 4. Bradford's law plot of sources, showing cumulative articles against source rank (log scale) and the three Bradford zones

Table 3. Most productive authors in research on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Rank	Author	Affiliation	Articles	Fractional count	TC	*h*-index	First year
1	Ni, Bing-Jie	University of Technology Sydney, Australia	19	3.29	2,231	17	2019
2	Wei, Wei	University of Technology Sydney, Australia	12	2.42	1,893	12	2019
3	Dai, Xiaohu	Tongji University, China	10	1.58	1,185	8	2019
3	Mendoza-Roca, J.A.	Universitat Politècnica de València, Spain	10	2.18	305	7	2020
3	Bes-Piá, M.A.	Universitat Politècnica de València, Spain	10	2.18	305	7	2020
6	Gao, Pin	Donghua University, China	9	1.79	472	5	2020
7	Li, Lu	Institute of Hydrobiology, Chinese Academy of Sciences, China	8	1.60	740	8	2020
7	Song, Kang	Institute of Hydrobiology, Chinese Academy of Sciences, China	8	1.60	740	8	2020
7	Dhar, Bipro Ranjan	University of Alberta, Canada	8	2.28	252	7	2022
7	Jachimowicz, Piotr	University of Warmia and Mazury in Olsztyn, Poland	8	2.48	153	6	2022
7	Cydzik-Kwiatkowska, Agnieszka	University of Warmia and Mazury in Olsztyn, Poland	8	2.48	153	6	2022

Notes: Authors were disambiguated using Scopus Author IDs; all authors with at least eight articles are listed. Fractional count = Sum of $1/n$ for each article, where n is the number of co-authors; TC = Total citations (Scopus "Cited by," search date November 13, 2026); *h*-index = Local *h*-index calculated from articles in the dataset; First year = Year of the author's first article in the dataset; Affiliation = Institution most frequently listed for the author across the dataset.



Figure 5. Production over time of the most productive authors (disambiguated by Scopus Author ID), 2019–2026. Bubble size and labels give the number of articles per year; colour gives total citations per year.

3.5. Institutional and country contributions

Chinese institutions dominated the list of productive affiliations, occupying 8 of the top 10 positions (Table 4). The Chinese Academy of Sciences (33 articles) and Tongji University (29) led, followed by Harbin Institute of Technology (20). The University of Technology Sydney (17 articles, 86.76 citations per article) and Universitat Politècnica de València (14) were the only institutions outside China in the top 10.

By corresponding author, China contributed 335 articles (51.9%), followed by Spain (33), the United States of America (USA; 26) and Italy (21) (Tables 5 & 6). The share of multi-country publications varied considerably: 38.1% for Italy and 38.5% for Iran, but 19.1% for China and 5.6% for Turkey, indicating that the largest producers work mainly within national networks. Citation impact showed a different pattern from output. China accumulated the most citations (14,526) but averaged 43.4 citations per article, whereas Finland's 12 articles averaged 399.4 citations per article, driven by the early Helsinki studies of removal by conventional and advanced treatment (Lares *et al.*, 2018; Talvitie, Mikola, Koistinen, Setälä, 2017; Talvitie, Mikola, Setälä, *et al.*, 2017). Ireland's 1,005 citations came from a single study of microplastics in treated sewage sludge (Mahon *et al.*, 2017). Geographical coverage was narrow. Only 7 of the 645 articles included an author affiliated with an African institution, and 9 included an author from Latin America, although sludge reuse in agriculture and decentralised treatment are widespread in both regions.

Table 4. Top 10 most productive affiliations in research on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Rank	Affiliation	Country	Articles	%	TC	TC/article
1	Chinese Academy of Sciences	China	33	5.12	2,513	76.15
2	Tongji University	China	29	4.50	2,721	93.83
3	Harbin Institute of Technology	China	20	3.10	714	35.70
4	University of Technology Sydney	Australia	17	2.64	1,475	86.76
5	Chongqing University	China	15	2.33	1,075	71.67
5	Hohai University	China	15	2.33	567	37.80
5	Beijing University of Technology	China	15	2.33	368	24.53
8	Universitat Politècnica de València	Spain	14	2.17	452	32.29
9	University of Chinese Academy of Sciences	China	13	2.02	1,266	97.38
9	Shandong University	China	13	2.02	810	62.31

Notes: Articles = Number of distinct articles with at least one author from the institution (each article counted once per institution, irrespective of the number of co-authors from that institution); % = Share of the 645 articles; TC = total citations (Scopus "Cited by", search date November 13, 2026). Institution names were harmonised at the university level from the Scopus Affiliations field (e.g., Harbin Institute of Technology includes its Shenzhen campus); the Chinese Academy of Sciences and the University of Chinese Academy of Sciences are reported separately as listed in Scopus.

3.6 Most cited documents

The most cited articles are dominated by full-scale studies of occurrence and removal published between 2015 and 2019 (Table 7). The two most cited, with 1,502 and 1,290 citations, compared conventional activated sludge (CAS) with MBRs and tertiary treatment (Lares *et al.*, 2018; Talvitie, Mikola, Koistinen, Setälä, 2017). Mass balances for individual plants in Italy and China (Liu *et al.*, 2019; Magni *et al.*, 2019), a comparison of an oxidation ditch with an MBR (Lv *et al.*, 2019), and a comparison of unit processes at three USA plants (Michielssen *et al.*, 2016) complete a group of studies that set the analytical and reporting conventions later work followed. Only 2 of the 10 articles go beyond removal: the study of sludge treatment effects on particle abundance and morphology (Mahon *et al.*, 2017), and the study showing that PVC microplastics inhibit methane production through bisphenol A leaching (Wei, Huang, Sun, Wang, *et al.*, 2019). The latter, which has a normalised citation score of 1.62, marks the start of process-interaction research that now dominates output.

Table 5. Most productive countries in research on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Rank	Country	Articles	%	SCP	MCP	MCP %
1	China	335	51.9	271	64	19.1
2	Spain	33	5.1	25	8	24.2
3	USA	26	4.0	20	6	23.1
4	Italy	21	3.3	13	8	38.1
5	Turkey	18	2.8	17	1	5.6
6	Canada	16	2.5	14	2	12.5
7	India	16	2.5	14	2	12.5
8	Iran	13	2.0	8	5	38.5
9	Korea	13	2.0	10	3	23.1
10	Poland	13	2.0	9	4	30.8

Notes: Countries are attributed to the corresponding author's affiliation. % = Share of the 645 articles; SCP = Single-country publications (all authors from one country); MCP = Multi-country publications (at least one co-author from another country); MCP % = (MCP/articles) × 100. Source: Biblioshiny (bibliometrix) Most Relevant Countries by Corresponding Author and Most Cited Countries outputs.

Table 6. Most cited countries in research on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Rank	Country	TC	Average citations per article
1	China	14,526	43.4
2	Finland	4,793	399.4
3	Spain	1,596	48.4
4	Australia	1,224	122.4
5	USA	1,134	43.6
6	Italy	1,072	51.0
7	Ireland	1,005	1005.0
8	Turkey	660	36.7
9	Thailand	595	49.6
10	United Kingdom	441	40.1

Notes: Countries are attributed to the corresponding author's affiliation. TC = Total citations (Scopus "Cited by", search date November 13, 2026). The high average citations of Finland (12 articles) and Ireland (1 article) reflect a small number of highly cited early studies. Source: Biblioshiny (bibliometrix) Most Relevant Countries by Corresponding Author and Most Cited Countries outputs.

Table 7. Top 10 most globally cited articles on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Rank	Reference	Title	Key finding	TC	TC/year	NTC
1	(Talvitie, Mikola, Koistinen, Setälä, 2017)	Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies	Four Finnish WWTPs: MBR removed 99.9% of MPs; tertiary rapid sand filtration 97%, dissolved air flotation 95%, and disc filter 40%–98.5%.	1,502	150.20	2.44
2	(Lares *et al.*, 2018)	Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology	Municipal CAS plant retained 98.3% of MPs, mostly before the activated sludge stage; pilot MBR permeate had 0.4 vs. 1.0 MP/L in CAS effluent.	1,290	143.33	3.00
3	(Mahon *et al.*, 2017)	Microplastics in sewage sludge: Effects of treatment	Sludge from 7 Irish WWTPs held 4,196–15,385 MPs/kg dw; lime stabilisation sheared particles, whereas anaerobic digestion was associated with lower MP abundance.	1,005	100.50	1.64
4	(Talvitie, Mikola, Setälä, *et al.*, 2017)	How well is microlitter purified from wastewater? – A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant	Advanced WWTP (activated sludge + biologically active filter) retained >99% of microlitter; ~80% of removed microlitter ended up in dried sludge, and ~20% returned via reject water.	754	75.40	1.23
5	(Magni *et al.*, 2019)	The fate of microplastics in an Italian Wastewater Treatment Plant	Large Italian WWTP removed 84% of MPs (from 2.5 to 0.4 MPs/L) yet released ~160 million MPs/day; MPs accumulated in activated sludge (113 MPs/g dw).	623	77.88	2.27
6	(Liu *et al.*, 2019)	Transfer and fate of microplastics during the conventional activated sludge process in one wastewater treatment plant of China	Chinese CAS plant removed 64.4% of MPs (from 79.9 to 28.4 n/L); removed MPs were transferred to sludge (240.3 n/g dw), with polyamide dominant.	546	68.25	1.99
7	(Lv *et al.*, 2019)	Microplastics in a municipal wastewater treatment plant: Fate, dynamic distribution, removal efficiencies, and control strategies	Full-scale MBR removed 99.5% (mass) and 82.1% (number) of MPs vs. 97% and 53.6% for an oxidation ditch; removed MPs accumulated in sludge.	509	63.63	1.85
8	(Talvitie *et al.*, 2015)	Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea	Fibres were removed mainly in primary sedimentation and particles in secondary sedimentation; biological filtration improved removal, but effluent still exceeded receiving-water levels.	487	40.58	1.00
9	(Wei, Huang, Sun, Wang, *et al.*, 2019)	Polyvinyl Chloride Microplastics Affect Methane Production from the Anaerobic Digestion of Waste Activated Sludge through Leaching Toxic Bisphenol-A	PVC MPs at ≥20 particles/g TS inhibited methane production from waste activated sludge (to 75.8%–90.6% of control) via bisphenol A leaching that impaired hydrolysis–acidification.	445	55.63	1.62
10	(Michielssen *et al.*, 2016)	Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed	Removal of small anthropogenic litter was 95.6% (activated sludge), 97.2% (sand filtration), and 99.4% (MBR); fibres dominated effluents, and the fate of retained particles in sludge remained unresolved.	416	37.82	1.00

Notes: TC = Total citations in Scopus (search date November 13, 2026); TC/year = Total citations divided by the number of years since publication, including the publication year; NTC = Normalised total citations, i.e., total citations divided by the mean total citations of articles in the dataset published in the same year. Citation metrics are from Biblioshiny (bibliometrix) Most Global Cited Documents output; titles are from the Scopus records; key findings are summarised from each article's abstract.

Abbreviations: CAS: Conventional activated sludge; dw: Dry weight; MBR: Membrane bioreactor; MP: Microplastic; PVC: Polyvinyl chloride; TS: Total solids; WWTP: Wastewater treatment plant.

3.7. Keyword analysis and research hotspots

Of 1,375 author keywords, 58 occurred at least eight times and formed four clusters (Figure 6; Tables 8 & S4). The most frequent keywords after the search term were microbial community (73 occurrences), anaerobic digestion (72), WWTPs (65), sewage sludge (63) and constructed wetland (52).

Cluster 1 (red, 24 keywords, mean average-publication-year 2023.44) covers the occurrence, fate, and removal of microplastics in WWTPs and sewage sludge. It combines plant-scale terms (WWTPs, wastewater treatment, effluent, tertiary treatment, removal efficiency) with polymer and morphology terms (microfibres, PE, polyethylene terephthalate (PET), polypropylene [PP]), the analytical term Fourier-transform infrared (FTIR) spectroscopy, and degradation terms (biodegradation, plastic biodegradation, plastisphere, composting). Cluster 2 (green, 12 keywords, 2024.09) groups MBRs, membrane fouling, biofilm, aerobic granular sludge, and metagenomics with biodegradable microplastics, polylactic acid (PLA), adsorption, antibiotics, and heavy metals. Cluster 3 (blue, 12 keywords, 2023.91) brings together anaerobic digestion, waste activated sludge, and methane production with ARGs, horizontal gene transfer, functional genes, extracellular polymeric substances (EPS), and ageing. Cluster 4 (yellow, 10 keywords, 2023.48) links nanoplastics and PS with activated sludge, constructed wetlands, sequencing batch reactors, and the nitrogen-cycle terms nitrification, denitrification, nutrient removal, and nitrogen metabolism.

The average publication year of each keyword (Tables 8 & S4) separates older and newer themes. The oldest keywords were effluent (2021.75), nitrification (2022.56), PS (2022.71), sewage sludge (2022.77), activated sludge (2022.78), and MBR (2022.88), corresponding to early plant surveys and the first exposure experiments in activated sludge. The most recent were heavy metals (2025.30), biological treatment (2025.00), biodegradable microplastics (2024.82), micro- and nanoplastics (2024.78), PS microplastics (2024.75), antibiotics (2024.73), microplastic removal (2024.70), plastisphere (2024.65), and horizontal gene transfer (2024.62). The direction of travel is from describing where microplastics go in a treatment plant towards asking what they do inside it, with growing attention to co-contaminants, resistance genes, and polymers designed to degrade.

Table 8. Keyword clusters identified using co-occurrence analysis of author keywords in research on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Cluster	Research theme	*n*	Mean APY	Keywords (occurrences; total link strength; APY)
1 (Red)	Occurrence, fate, and removal of microplastics in WWTPs and sewage sludge	24	2023.44	Microplastics (359; 623; 2023.4); WWTPs (65; 135; 2023.0); sewage sludge (63; 130; 2022.8); wastewater (37; 78; 2023.0); wastewater treatment (37; 67; 2022.9); biodegradation (33; 55; 2023.6); removal efficiency (26; 57; 2023.7); polyethylene terephthalate (24; 57; 2023.6); plastisphere (20; 40; 2024.7); composting (14; 31; 2023.1); domestic wastewater (12; 28; 2023.9); microfibres (12; 28; 2023.6); FTIR spectroscopy (12; 27; 2023.7); polyethylene (12; 27; 2023.3); emerging contaminants (12; 17; 2024.7); polypropylene (10; 26; 2023.8); biological treatment (10; 20; 2025.0); microplastic removal (10; 19; 2024.7); tertiary treatment (8; 24; 2023.2); effluent (8; 23; 2021.8); nature-based solutions (8; 17; 2024.1); plastic biodegradation (8; 13; 2024.5); plastic pollution (8; 11; 2024.6); microplastic pollution (8; 10; 2024.5)
2 (Green)	Membrane, biofilm systems, and biodegradable microplastics	12	2024.09	Membrane bioreactor (24; 52; 2022.9); biofilm (21; 46; 2023.9); metagenomics (17; 40; 2024.1); membrane fouling (15; 39; 2024.4); polylactic acid (13; 32; 2024.4); aerobic granular sludge (13; 26; 2024.0); antibiotics (11; 27; 2024.7); biodegradable microplastics (11; 19; 2024.8); heavy metals (10; 23; 2025.3); toxicity (10; 22; 2023.4); micro- and nanoplastics (9; 16; 2024.8); adsorption (8; 15; 2023.9)
3 (Blue)	Anaerobic sludge digestion, EPS, and the resistome	12	2023.91	Anaerobic digestion (72; 150; 2023.8); antibiotic resistance genes (45; 102; 2024.2); extracellular polymeric substances (37; 71; 2024.0); waste activated sludge (34; 69; 2023.3); methane production (20; 54; 2023.3); ageing (16; 28; 2024.5); nitrogen removal (13; 34; 2023.9); polyethylene microplastics (10; 24; 2023.6); functional genes (9; 21; 2024.4); horizontal gene transfer (8; 21; 2024.6); anaerobic granular sludge (8; 15; 2023.4); polystyrene microplastics (8; 14; 2024.8)

(*Cont'd...*)

Table 8. (*Continued*)

Cluster	Research theme	*n*	Mean APY	Keywords (occurrences; total link strength; APY)
4 (Yellow)	Nanoplastic effects on activated sludge, constructed wetlands, and nitrogen transformation	10	2023.48	Microbial community (73; 181; 2023.7); constructed wetland (52; 98; 2023.9); activated sludge (41; 98; 2022.8); nanoplastics (37; 85; 2023.5); polystyrene (14; 35; 2022.7); sequencing batch reactor (11; 29; 2023.5); nitrogen metabolism (10; 16; 2024.1); nutrient removal (9; 26; 2023.3); nitrification (9; 25; 2022.6); denitrification (8; 18; 2023.5)

Notes: Analysis was performed in VOSviewer using author keywords with full counting and association-strength normalisation; keyword variants were harmonised with a thesaurus file and generic terms were excluded. Of 1,375 keywords, 58 met the minimum occurrence threshold of 8, forming 4 clusters. Occurrences and total link strength are as reported by VOSviewer. APY = Average publication year of the articles containing each keyword, calculated from the dataset; mean APY = Occurrence-weighted mean for the cluster. Within each cluster, keywords are listed in descending order of occurrence. Cluster colours correspond to Figure 6.
Abbreviations: EPS: Extracellular polymeric substances; FTIR: Fourier-transform infrared; WWTPs: Wastewater treatment plants.

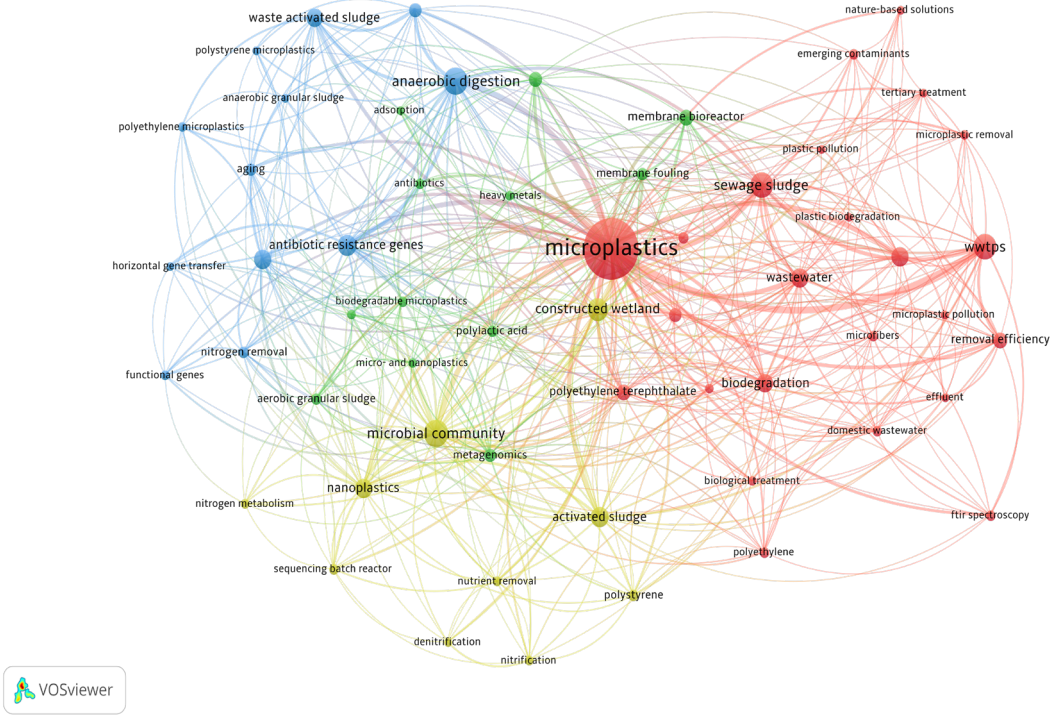

Figure 6. Co-occurrence analysis of author keywords (58 keywords with at least eight occurrences). Network visualisation showing four clusters. Node size reflects occurrence and line thickness reflects link strength.
Abbreviation: WWTPs: Wastewater treatment plants.

3.8. Conceptual structure

The thematic map placed anaerobic digestion, sewage sludge, and ARGs in the motor quadrant, combining high centrality (1.446) with high density (27.660) (Figure 7; Table 9). This is the most developed and most connected theme in the field. The theme led by microbial community, constructed wetland, and activated sludge had the highest centrality (1.741) and the largest frequency (573), and sat on the boundary between the motor and basic quadrants, marking it as a broad foundation that is still developing internally. The WWTP theme, including wastewater treatment, biodegradation, removal efficiency, MBR, membrane fouling, and microfibres, fell in the basic quadrant: central to the field but with weaker internal links, because it gathers plant surveys that use different methods and report different metrics.

Smaller themes lay on the periphery. Plastic biodegradation, earthworms, and vermicomposting

formed a well-developed but weakly connected theme on the niche–motor boundary, and sludge management, biochar, and circular economy formed a niche theme. PET hydrolase and microparticles appeared as emerging or declining themes, each based on only four keyword occurrences. Read together with the average publication years, which place enzymatic and biodegradable-polymer topics among the most recent keywords, these are better interpreted as emerging than declining. They are, however, too small to support firm conclusions.

Table 9. Themes identified in the thematic map of author keywords in research on micro- and nanoplastics in biological wastewater and sludge treatment (2015–2026)

Quadrant	Theme	Keywords	Callon centrality	Callon density	Freq.
Motor	Anaerobic digestion	Anaerobic digestion; sewage sludge; antibiotic resistance genes	1.446	27.660	463
Motor/basic (boundary)	Microbial community	Microbial community; constructed wetland; activated sludge	1.741	25.565	573
Basic	WWTPs	WWTPs; wastewater treatment; biodegradation; removal efficiency; membrane bioreactor; membrane fouling; domestic wastewater; FTIR spectroscopy; microfibers	1.002	24.488	390
Niche/motor (boundary)	Plastic biodegradation	Plastic biodegradation; earthworms; vermicomposting	0.168	28.611	16
Niche	Sludge management	Sludge management; biochar; circular economy	0.000	37.037	10
Emerging or declining	PETase	PETase	0.000	25.000	4
Emerging or declining	Microparticles	Microparticles	0.167	25.000	4

Notes: Thematic map generated in Biblioshiny (bibliometrix) from author keywords (250 words; Walktrap clustering), with keyword variants harmonised by a synonyms file and the search term ("microplastics") and generic terms removed. Callon centrality measures the strength of a theme's links to other themes (relevance); Callon density measures the strength of internal links (development); Freq. = Total occurrences of keywords in the theme. Quadrant positions follow the thematic map (Figure 7); themes near the axes are reported as boundary themes. Keywords for the WWTPs theme are from the Biblioshiny terms export; for other themes, the three label keywords shown on the map are listed.
Abbreviations: FTIR: Fourier-transform infrared; PETase: Polyethylene terephthalate hydrolase; WWTPs: Wastewater treatment plants.

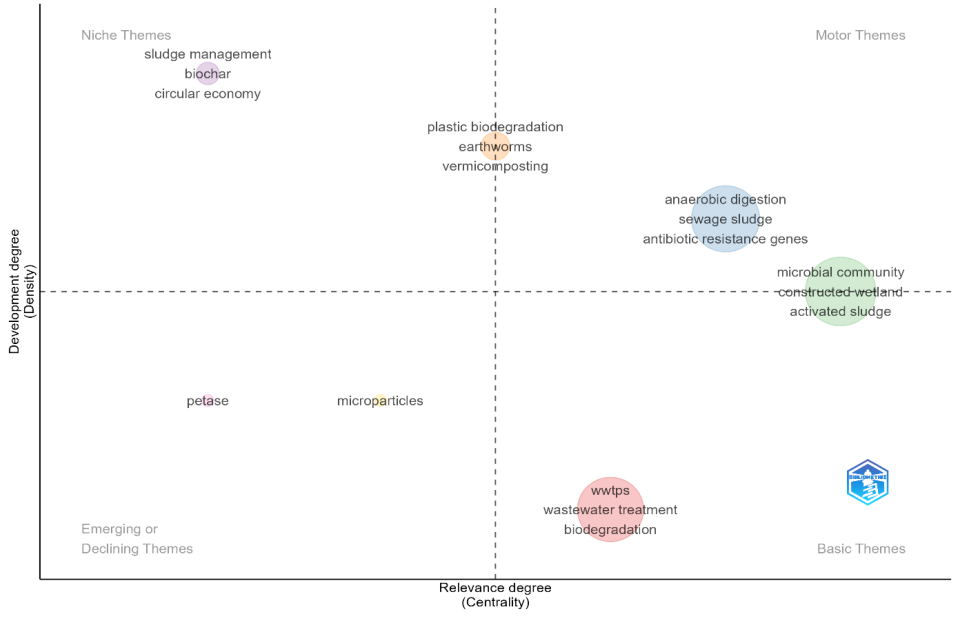

Figure 7. Thematic map of author keywords based on Callon centrality (relevance) and density (development). Bubble size reflects keyword occurrence.

4. Discussion

The bibliometric results show a field that grew rapidly after 2021 and shifted from measuring removal towards studying interactions between particles and treatment biology. The sections below assess the evidence under each of the main themes.

4.1. Removal performance across biological treatment trains

Reported removal efficiencies are summarised in Table 10. For CAS plants, they range widely, from 64.4% at a Chinese plant (Liu *et al.*, 2019) and 84% at an Italian plant (Magni *et al.*, 2019) to between 95.6% and more than 99% in Finnish and USA plants (Lares *et al.*, 2018; Michielssen *et al.*, 2016; Talvitie, Mikola, Setälä, *et al.*, 2017). Much of this variation reflects plant design and analytical choices rather than differences in biological performance. Several studies found that most particles are removed before the biological stage. Fibres were removed mainly in primary sedimentation and synthetic particles mainly in secondary sedimentation (Talvitie *et al.*, 2015), and screening and grit removal alone captured 69%–79% of the influent load at three Australian plants (Ziajahromi *et al.*, 2021). The biological reactor is therefore one step in a sequence, and its specific contribution is rarely separated from that of the clarifiers.

Membrane bioreactors consistently reported the lowest effluent concentrations. A full-scale MBR removed 99.9% of microplastics, reducing the concentration from 6.9 to 0.005 particles/L (Talvitie, Mikola, Koistinen, Setälä, 2017), and an MBR removed 99.4% of small anthropogenic litter compared with 95.6% for activated sludge (Michielssen *et al.*, 2016). Comparative studies, however, show that the advantage depends on how removal is expressed. In a full-scale plant in eastern China, the MBR removed 99.5% of microplastics by mass but 82.1% by number, compared with 97% and 53.6% for an oxidation ditch (Lv *et al.*, 2019). In another full-scale plant, MBR removal (79.01%) was not statistically different from that by rapid sand filtration (75.49%), and fibres were removed far less efficiently than particles by both (Bayo *et al.*, 2020). Removal by number is sensitive to the smallest size class that a method can detect, and plants that perform well when particles above 100 μm are counted may perform less well when particles down to 10 μm are included. One recent study using focal plane array micro-FTIR down to 10 μm showed that a well-designed modern plant with tertiary sand filtration can reduce effluent concentrations to levels comparable with the receiving marine waters (Chand *et al.*, 2024), suggesting that good design matters more than the choice of a particular biological process.

Constructed wetlands perform well as polishing stages. A horizontal subsurface flow wetland used for tertiary treatment removed 88% of microplastics, from 6.45 to 0.77 particles/L (Q. Wang *et al.*, 2020). In microcosms, horizontal subsurface flow wetlands retained all added microplastics, while surface flow wetlands retained 81.63% and released larger fragments and fibres preferentially (Y. Chen *et al.*, 2021). More than 97% of PS nanoplastics were retained in laboratory wetlands, with the sand biofilm as the main sink (Y. Ma *et al.*, 2021). Retention in a wetland raises a question that conventional plants also face: particles accumulate in the substrate and biofilm, and their long-term fate and effects on the treatment function of the wetland remain poorly known.

4.2. Fate in the sludge line

Because the water line moves most particles into solids, the sludge line determines the final environmental outcome. Concentrations reported in sludge cover a wide range, from 113 particles/g dw in recycled activated sludge in Italy (Magni *et al.*, 2019) to 240.3 particles/g in dewatered sludge in China (Liu *et al.*, 2019) and 37.7–286.5 particles/g across a UK sludge treatment stream (Harley-Nyang *et al.*, 2022). Methods differ substantially between studies; therefore, these values are not strictly comparable. An intercomparison of six extraction procedures using spiked wastewater and digested sludge found marked differences in recovery and argued that unvalidated results should be treated as rough estimates (Lares *et al.*, 2019).

There is little evidence that conventional sludge treatment removes conventional polymers. In Irish sludge, lime stabilisation sheared particles and increased the abundance of small size classes, thermal drying caused melting and blistering, and anaerobic digestion was associated with lower abundance (Mahon *et al.*, 2017). Controlled tests do not support digestion as a removal route. Mesophilic and thermophilic digestion produced surface changes in eight commodity polymers, including smoothing of PE and PP and embrittlement of PS and PVC, but did not degrade them substantially (Lessa Belone *et al.*, 2024). At a centralised biogas plant, more than 99% of microplastics were retained in the solid fraction of the dewatered digestate, the fraction most often returned to farmland (Yli-Rantala *et al.*, 2025). Digestion therefore changes the form of microplastics more than their amount, and fragmentation may increase particle numbers.

Aerobic processes at high temperature show more promise. Hyperthermophilic composting at full scale removed 43.7% of microplastics from sewage sludge in 45 days, and its inoculum degraded 7.3% of PS microplastics at 70 °C in 56 days, about 6.6 times more

than a conventional thermophilic inoculum (Z. Chen *et al.*, 2020). Vermicomposting of digested sludge with *Eudrilus eugeniae* reduced the abundance of PP and high-density polyethylene (HDPE) particles by 22%–78% over 14 weeks, with larger reductions for smaller particles (Ragoobur *et al.*, 2022). These studies measured disappearance of particles above a size threshold, and a reduction in counts may reflect fragmentation below that threshold as well as mineralisation. Neither confirmed complete conversion to carbon dioxide or biomass, which is the evidence that would be needed to recommend either process as a removal route.

Table 10. Reported removal of microplastics by biological treatment trains and process units

Process	Scale	Removal	Basis and notes	Reference
CAS	Full scale, China	64.4%	Number; removed particles transferred to sludge	(Liu *et al.*, 2019)
CAS	Full scale, Italy	84%	Number; ~160 million particles/day still discharged	(Magni *et al.*, 2019)
Hybrid suspended/attached growth	Full scale, India	~80%	Number	(Parashar & Hait, 2022)
CAS (whole plant)	Full scale	98.3%	Number; most removal before the biological stage	(Lares *et al.*, 2018)
Activated sludge + biologically active filter	Full-scale, tertiary plant	>99%	Number (microlitter); ~80% of removed load in dried sludge	(Talvitie, Mikola, Setälä, *et al.*, 2017)
Three plants, screening to effluent	Full scale, Australia	98.2%–99.8%	Number; 69%–79% removed at screening and grit removal	(Ziajahromi *et al.*, 2021)
Activated sludge/sand filtration/MBR	Full scale and pilot	95.6%/97.2%/99.4%	Number (small anthropogenic litter); fibres dominate effluent	(Michielssen *et al.*, 2016)
MBR; tertiary RSF, DAF, disc filter	Full scale	99.9%; 97%, 95%, 40%–98.5%	Number	(Talvitie, Mikola, Koistinen, Setälä, 2017)
Oxidation ditch vs. MBR	Full scale, eastern China	OD 97%/53.6%; MBR 99.5%/82.1%	Mass/number	(Lv *et al.*, 2019)
MBR vs. RSF	Full scale	79.01% vs. 75.49%	Number; fibres 57.65% vs. 53.83%	(Bayo *et al.*, 2020)
MBBR vs. activated sludge + ultrafiltration	Two full-scale plants	PE 94.9% vs 97.5%; PDMS 67.4% vs. 87.8%	Mass (^{1}H NMR)	(Giannattasio *et al.*, 2026)
Horizontal subsurface flow CW (tertiary)	Full scale	88% (CW); 98% (whole plant)	Number	(Q. Wang *et al.*, 2020)
Surface flow vs. horizontal subsurface flow CW	Microcosm	81.63% vs. 100%	Number; spiked particles 0.5–4 mm	(Y. Chen *et al.*, 2021)
CW with sand substrate	Laboratory	>97%	Polystyrene nanoplastics retained, mainly in sand biofilm	(Y. Ma *et al.*, 2021)
Algal-bacterial granular sludge	Laboratory	>96%	Spiked polystyrene, 50 μm	(Huang *et al.*, 2022)

Note: Values are as reported by each study; size limits, extraction methods, and units differ between studies, so values are not directly comparable. Abbreviations: CAS: Conventional activated sludge; CW: Constructed wetland; DAF: Dissolved air flotation; ^{1}H NMR: Proton nuclear magnetic resonance; MBBR: Moving bed biofilm reactor; MBR: Membrane bioreactor; OD: Oxidation ditch; PDMS: Polydimethylsiloxane; PE: Polyethylene; RSF: Rapid sand filtration.

4.3. Mechanisms of retention and transformation

The mechanisms behind retention in biological units are better described than quantified. Sedimentation in primary and secondary clarifiers removes larger and denser particles (Liu *et al.*, 2019; Talvitie *et al.*, 2015), and incorporation into flocs governs the fate of smaller ones. PS nanoparticles interacted with carbonyl and amide groups in EPS, altered the secondary structure of EPS proteins, and promoted bioflocculation of activated sludge (Feng *et al.*, 2018). In an MBR, microplastics reduced floc size and hydrophobicity, apparently by taking up the divalent cations that bridge floc structures, but they also scoured the membrane surface, so fouling did not worsen over four months (Maliwan *et al.*, 2021). Retention is therefore governed by surface chemistry and floc structure, and the

same particle property can work in opposite directions in different parts of a process.

Particles are also changed by the treatment process. Polyamide (PA), PE, and PS passing through sewers, grit chambers, and aeration tanks gained oxygen-containing groups and specific surface area, and lost carbon, hydrogen, and glass transition temperature, all signs of chain scission and oxidation, and their capacity to adsorb cadmium changed accordingly (X. Li *et al.*, 2021). Biological fragmentation may also generate nanoplastics. *Comamonas testosteroni* KF-1, a wastewater isolate, fragmented PET pellets and increased the abundance of particles below 100 nm by 3.5 times over 30 days while hydrolysing PET oligomers to terephthalate (Wilkes *et al.*, 2024). Partial biodegradation can therefore create smaller particles before it removes any polymer mass, and this needs to be considered when biodegradation is proposed as a treatment.

Biodegradation of conventional polymers by activated sludge communities is real but slow. A consortium from activated sludge degraded 17% of PET by surface erosion without changing molecular weight (Torena *et al.*, 2021), and in sludge incubations about 52% of polyhydroxyalkanoate (PHA) degraded in 43 days while PLA and PVC did not degrade significantly (J. Ma *et al.*, 2022). Weight loss, FTIR changes, and surface erosion are common evidence, and few studies close the carbon balance. Without mineralisation data, it is difficult to separate true biodegradation from fragmentation or loss of particles during recovery.

4.4. Interactions with biological process performance

The largest and fastest-growing body of work concerns the effects of microplastics on the biology of treatment. The results are consistent in direction for some endpoints but strongly dependent on polymer, size, and dose. In activated sludge, five common polymers at up to 10,000 particles/L had little effect on nitrification and denitrification over three hours, but PVC raised nitrous oxide emission during denitrification 4.6-fold at the highest dose (L. Li *et al.*, 2020). In nitrifying sequencing batch reactors exposed to 1 mg/L microplastics together with triclosan, PE and PS caused no measurable inhibition, whereas PVC and PA led to loss of nitrification within 14 days (Z. Wang *et al.*, 2020). In constructed wetlands, PS microplastics first increased nitrogen removal by 3.9%–24.7% and then decreased it by 7.1%–41.3% as particles accumulated (Yang, He, *et al.*, 2022), and ammonium removal fell by 7.6%–71.2% depending on particle size and concentration (Yang, Zhang, *et al.*, 2022).

In anaerobic digestion, dose–response relationships are often non-monotonic. PVC at 10 particles/g total solids (TS) increased methane production by 5.9%, but at 20–60 particles/g TS it reduced methane production to 75.8%–90.6% of the control, an effect traced to bisphenol A leaching that inhibited hydrolysis and acidification (Wei, Huang, Sun, Wang, *et al.*, 2019). Polycarbonate improved methane production by up to 24.7% at 30 particles/g TS but reduced it by 8.09% at 200 particles/g TS, again through bisphenol A, which lowered intracellular reactive oxygen species at the lower dose and stimulated them at the higher dose (H. Chen *et al.*, 2023). Polyamide 6 increased methane production through the leaching of caprolactam (H. Chen *et al.*, 2021), whereas PE reduced it by 12.4%–27.5% at 100–200 particles/g TS through the induction of reactive oxygen species rather than additive leaching (Wei, Huang, Sun, Dai, & Ni, 2019). Size matters as much as polymer: 1 and 10 μm PS microplastics had no perceptible effect on methane production, while 50 nm nanoplastics reduced it by 15.5% by inhibiting acetate kinase (J. Wang *et al.*, 2022). An automated machine-learning analysis of published data likewise found that polymer type was more influential than particle diameter or concentration (Xu *et al.*, 2022).

Two conclusions follow. First, additives and their leaching explain much of the variation between polymers, so studies that report only polymer type and particle count are hard to compare. Second, the exposure concentrations used matter for interpretation. Particle-based doses in digestion studies (10–200 particles/g TS) overlap with the concentrations measured in real sludges (Harley-Nyang *et al.*, 2022; Liu *et al.*, 2019; Magni *et al.*, 2019), so effects reported at the lower end of that range are relevant to practice. Mass-based nanoplastic doses, such as 0.2 g/L in digesters (S.-F. Fu *et al.*, 2018) or 1–10 mg/L in wetlands (Y. Ma *et al.*, 2021), cannot yet be compared with field exposure because nanoplastic concentrations in real wastewater and sludge have not been measured. Effects at these doses demonstrate mechanisms but do not show that full-scale processes are at risk.

Pretreatment can offset some effects. PS nanoplastics at 100 and 150 μg/L reduced methane yield by 17.98% and 29.34%, respectively, and increased reactive oxygen species levels, but thermal hydrolysis of the sludge at 80 or 160 °C counteracted the loss of methane production (Azizi *et al.*, 2022). Studies of this kind, which look for operational responses rather than only document harm, are still uncommon.

4.5. Granular, biofilm, and algal-bacterial systems

Most effect studies use flocculent activated sludge or digested sludge, but the same questions apply to granular, biofilm, and algal-bacterial processes, where biomass structure depends on EPS and cell aggregation. Aerobic granular sludge tolerated 1 mg/L of PS micro- and nanoplastics, whereas 20–100 mg/L impaired granule integrity and reduced total nitrogen removal by 3.8%–17.8% for microplastics and 11.4%–22.8% for nanoplastics (B. Zhang *et al.*, 2023). PE microplastics at 20 and 200 particles/L increased reactive oxygen species and lactate dehydrogenase release in aerobic granules and disrupted cell structure (X. Zheng *et al.*, 2022). Another study found that PE did not worsen treatment but almost doubled alginate content, from 238.7 to 441.6 mg/g mixed liquor suspended solids (Jachimowicz *et al.*, 2022). PLA at 5–40 mg/L even strengthened granule stability (Song *et al.*, 2022). Increased EPS production appears to be a protective response that shields granules from larger particles but not from nanoplastics (B. Zhang *et al.*, 2023).

Anaerobic granules are more sensitive. Over 264 days, PVC at 15–150 particles/L reduced chemical oxygen demand removal by 13.2%–35.5% and methane production by 11.0%–32.3%, suppressed EPS secretion, and caused granule breakage (Y.-T. Zhang *et al.*, 2020). Inhibition of methane production increased from 6.7% to 16.2% as PS particle size rose from 0.5 to 150 μm (C. Wang *et al.*, 2022), and PVC nanoplastics at 50 μg/L made EPS proteins more hydrophilic and caused granules to disintegrate (P. Zheng *et al.*, 2024). Hydrochar mitigated the loss of methane production caused by a mixture of four polymers by 50.6% (Wei *et al.*, 2022). In anammox sludge, PVC at 0.1 g/L reduced nitrite removal by 19.2%, and biodegradable polybutylene succinate (PBS) was less harmful (Tang *et al.*, 2021).

Biofilm reactors have received far less attention. Only seven articles in the dataset concerned moving bed biofilm reactors (MBBRs) or similar attached-growth systems. In an MBBR, PE at 1,000 μg/L reduced ammonium and total nitrogen removal by 33.5% and 35.2%, respectively, and suppressed nitrifying and denitrifying enzyme activity (T. Wu *et al.*, 2024). At full scale, a plant using an MBBR removed 94.9% of PE by mass, close to the 97.5% achieved by activated sludge with ultrafiltration, but removed only 67.4% of the hydrophobic polymer polydimethylsiloxane (PDMS) (Giannattasio *et al.*, 2026). Algal-bacterial granules retained more than 96% of added PS microplastics with only small losses in chemical oxygen demand and phosphorus removal (Huang *et al.*, 2022), and in algal-bacterial biofilms, 5 μm particles caused the greatest damage (Gong *et al.*, 2023). Because attached-growth and algal-bacterial systems are common in small and decentralised plants, the shortage of data on them is a real gap.

4.6. Microplastics as vectors of antimicrobial resistance

Resistance genes form one of the most connected themes in the dataset, and the evidence that microplastics enrich them in treatment systems is fairly consistent. In activated sludge from three domestic plants, PE and PS particles developed biofilms enriched with *sul1*, *sul2* and *intI1* relative to sand, and gene abundance rose a further 1.2–4.5-fold when sulfamethoxazole was present; potential pathogens such as *Raoultella ornithinolytica* and *Stenotrophomonas maltophilia* were also selectively enriched (Pham *et al.*, 2021). In anaerobic digesters, PE variants raised ARG abundance by 4.5%–27.9% in a dose-dependent manner between 10 and 80 particles/g TS (Luo, Dai, Wei, *et al.*, 2023), and PE and PVC increased ARGs by 14.8% and 23.6%, respectively, by shifting specific host bacteria (Luo, Dai, Chen, *et al.*, 2023). PET microfibres increased extracellular ARGs in digesters 1.70-fold in absolute terms (L. Zhang *et al.*, 2022), and PS combined with sulfamethoxazole raised ARG abundance in aerobic granular sludge by 62.02% compared with sulfamethoxazole alone (Ji *et al.*, 2023). Nanoplastics released by washing synthetic textiles also enriched ARGs, virulence genes, and mobile genetic elements in anaerobic sludge (Yin *et al.*, 2025).

Most of these results are relative increases measured in laboratory reactors, often with spiked antibiotics and particle loads at the upper end of the field range. Few studies show that resistance acquired on particles in a treatment plant survives discharge and transfers to environmental or clinical bacteria, and quantitative risk assessment is almost absent. Linking particle-associated resistomes in effluent and biosolids to resistance in receiving waters and soils is the next necessary step.

4.7. Nanoplastics and biodegradable plastics

Nanoplastics and biodegradable polymers are among the newest themes in the dataset, and both raise methodological problems. Most nanoplastic studies use spherical PS particles at mg/L concentrations, which are convenient to dose and detect but may not represent the irregular, aged, and chemically diverse particles formed in practice. Their effects on nitrogen removal and digestion can be substantial. In constructed wetlands, PS nanoplastics penetrated cell membranes, disturbed reactive oxygen species balance, and reduced nitrogen removal (Yang *et al.*, 2020), and 50 nm particles inhibited methanogenesis where larger particles did not (J. Wang *et al.*, 2022). The

ability to measure nanoplastics in real influent, sludge, and digestate is the main limitation for assessing whether these effects occur at full scale.

Biodegradable plastics are often assumed to be harmless once they reach a digester, but recent work shows that this depends on the polymer. Under mesophilic anaerobic conditions, polyhydroxybutyrate (PHB), poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), and cellulose diacetate degraded to methane with only transient microplastic formation, whereas polybutylene succinate-co-adipate (PBSA) and PLA hydrolysed incompletely and produced abundant persistent microplastics, and polybutylene adipate-co-terephthalate (PBAT) and polycaprolactone (PCL) fragmented into small particles with little methanogenesis (Jin *et al.*, 2026). PLA co-digested with kitchen waste deformed and fragmented without increasing methane yield (Lu *et al.*, 2022). Polymer chemistry therefore decides whether a "biodegradable" plastic is mineralised in a sludge digester or becomes a new source of microplastics, and certification under composting conditions is not a reliable guide to behaviour in anaerobic sludge treatment.

4.8. Research gaps and priorities

Analytical comparability is the top priority. Recovery rates differ widely between extraction methods (Lares *et al.*, 2019), lower size limits vary from about 10 μm to several hundred micrometres, and results are reported by number, mass, or both. Spike-recovery tests, reported size limits, and paired reporting of number and mass should be standardised, particularly for sludge, where matrix effects are strongest.

Nanoplastics need to be measured, not only dosed. Exposure studies have outpaced measurement, and until nanoplastic concentrations in influent, mixed liquor, digestate, and effluent are known, effect thresholds from laboratory studies cannot be placed in context. The fragmentation of particles during biological treatment and sludge processing (Mahon *et al.*, 2017; Wilkes *et al.*, 2024) suggests that treatment itself may be a source of nanoplastics.

Exposure studies should use realistic concentrations and particles. Weathered, irregular particles of the polymers that dominate influent, tested over operational timescales in continuous reactors, would give more transferable results than short batch tests with pristine PS spheres. Additive content should be characterised, because leaching explains much of the variation between polymers (H. Chen *et al.*, 2021, 2023; Wei, Huang, Sun, Wang, *et al.*, 2019).

Full-scale mass balances across the whole sludge line, from primary sludge through digestion, dewatering, and land application, are still rare. Studies that follow both particles and resistance genes into biosolids and soil would connect the treatment and environmental literatures (Keller *et al.*, 2020; Yli-Rantala *et al.*, 2025). Claims of biodegradation in composting, vermicomposting, or reactors should be supported by mineralisation data rather than particle counts alone.

Finally, research capacity is unevenly distributed. More than half of the articles had a corresponding author in China, and Africa and Latin America together contributed fewer than 20 articles, although waste stabilisation ponds, decentralised systems, and agricultural reuse of sludge and wastewater are common in both regions. Evidence from these systems, and from low-cost biological treatment in general, is needed before results from large activated sludge plants in China, Europe, and North America are generalised.

5. Conclusion

Research on micro- and nanoplastics in biological wastewater and sludge treatment grew from a single article in 2015 to more than 130 a year by 2025, with most output from China and a small core of environmental journals. The field began with plant surveys showing that conventional treatment retains most microplastics, and has since moved towards the effects of particles on sludge biology, resistance genes, and digestion, which now form its most developed theme. The evidence shows that high removal in the water line is achieved mainly by transferring particles to sludge, that anaerobic digestion does not remove conventional polymers from sludge, and that effects on nitrification, denitrification, and methanogenesis depend on polymer, size, dose, and additives. Many effects have been shown at concentrations above those measured in practice, and nanoplastic exposure remains unmeasured. Progress now depends on harmonised analytical methods, measurement of nanoplastics in real matrices, realistic exposure studies, full-scale mass balances along the sludge line, mineralisation-based evidence of biodegradation, and wider geographical coverage of research.

Funding

This research was supported by the Universiti Teknologi Malaysia Fundamental Research Grant (UTMFR/23H66).

Acknowledgements

The authors would like to acknowledge the financial support provided by Universiti Teknologi Malaysia during the course of this study and the Malaysia International Scholarship for OJI support.

Conflict of interest

The authors have no financial or non-financial interests to declare.

Ethical approvals

Not applicable.

Clinical trial number

Not applicable.

Authors' contributions

Tirmizhi Munkaila Abubakar: Conceptualization, Methodology, Formal analysis, Data curation, Validation, Visualization, Investigation, Writing – original draft, Writing – review & editing.
Oloche Job Ibrahim: Data curation, Validation, Writing – review & editing.
Mustapha Abba: Writing – review & editing.
Bashar Haruna Gulumbe: Data curation, Writing – review & editing.
Abdullahi Adamu Faggo: Writing – review & editing.
Abdussamad Abubakar: Validation, Writing – review & editing.
Nurulfiza Mat Isa: Writing – review & editing, Supervision.
Nor Azimah Mohd Zain: Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing, Supervision. All authors reviewed and approved the final manuscript.

Data availability

The search log is provided in Table S1, the raw Scopus export in Table S2, and the cleaned dataset used for the analysis in Table S3. Table S4 presents the occurrences, total link strength, and average publication year of the 58 keywords included in the co-occurrence network.

References

Ahmed, S. F., Islam, N., Tasannum, N., Mehjabin, A., Momtahin, A., Chowdhury, A. A., Almomani, F., & Mofijur, M. (2024). Microplastic removal and management strategies for wastewater treatment plants. *Chemosphere*, *347*, 140648.

https://doi.org/10.1016/j.chemosphere.2023.140648

Alazaiza, M. Y. D., Alzghoul, T. M., Bashir, M. J. K., Ramu, M. B., Abu Amr, S. S., & Abushammala, M. F. M. (2025). Emerging trends in tackling microplastics in wastewater systems: Insights from a global research perspective. *Case Studies in Chemical and Environmental Engineering*, *11*, 101041.

https://doi.org/10.1016/j.cscee.2024.101041

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975.

https://doi.org/10.1016/j.joi.2017.08.007

Azizi, S. M. M., Haffiez, N., Zakaria, B. S., & Dhar, B. R. (2022). Thermal Hydrolysis of Sludge Counteracts Polystyrene Nanoplastics-Induced Stress during Anaerobic Digestion. *ACS ES&T Engineering*, *2*(7), 1306–1315.

https://doi.org/10.1021/acsestengg.1c00460

Bayo, J., López-Castellanos, J., & Olmos, S. (2020). Membrane bioreactor and rapid sand filtration for the removal of microplastics in an urban wastewater treatment plant. *Marine Pollution Bulletin*, *156*, 111211.

https://doi.org/10.1016/j.marpolbul.2020.111211

Bradford, S. C. (1985). Sources of information on specific subjects 1934. *Journal of Information Science*, *10*(4), 176–180.

https://doi.org/10.1177/016555158501000407

Callon, M., Courtial, J. P., & Laville, F. (1991). Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry. *Scientometrics*, *22*(1), 155–205.

https://doi.org/10.1007/BF02019280

Chand, R., Iordachescu, L., Bäckbom, F., Andreasson, A., Bertholds, C., Pollack, E., Molazadeh, M., Lorenz, C., Nielsen, A. H., & Vollertsen, J. (2024). Treating wastewater for microplastics to a level on par with nearby marine waters. *Water Research*, *256*, 121647.

https://doi.org/10.1016/j.watres.2024.121647

Chen, H., Tang, M., Yang, X., Tsang, Y. F., Wu, Y., Wang, D., & Zhou, Y. (2021a). Polyamide 6 microplastics facilitate methane production during anaerobic digestion of waste activated sludge. *Chemical Engineering Journal*, *408*, 127251.

https://doi.org/10.1016/j.cej.2020.127251

Chen, H., Zou, Z., Tang, M., Yang, X., & Tsang, Y. F. (2023). Polycarbonate microplastics induce oxidative stress in anaerobic digestion of waste activated sludge by leaching bisphenol A. *Journal of Hazardous Materials*, *443*, 130158.

https://doi.org/10.1016/j.jhazmat.2022.130158

Chen, Y., Li, T., Hu, H., Ao, H., Xiong, X., Shi, H., & Wu, C. (2021b). Transport and fate of microplastics in constructed wetlands: A microcosm study. *Journal of Hazardous Materials*, *415*, 125615.

https://doi.org/10.1016/j.jhazmat.2021.125615

Chen, Z., Zhao, W., Xing, R., Xie, S., Yang, X., Cui, P., Lü, J., Liao, H., Yu, Z., Wang, S., & Zhou, S. (2020). Enhanced in situ biodegradation of microplastics in sewage sludge using hyperthermophilic composting technology. *Journal of Hazardous Materials*, *384*, 121271.

https://doi.org/10.1016/j.jhazmat.2019.121271

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., &

Herrera, F. (2011). An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of Informetrics*, *5*(1), 146–166.

https://doi.org/10.1016/j.joi.2010.10.002

Feng, L.-J., Wang, J.-J., Liu, S.-C., Sun, X.-D., Yuan, X.-Z., & Wang, S.-G. (2018). Role of extracellular polymeric substances in the acute inhibition of activated sludge by polystyrene nanoparticles. *Environmental Pollution*, *238*, 859–865.

https://doi.org/10.1016/j.envpol.2018.03.101

Fu, B., Zhou, W., Chen, Y., Wu, Y., Gan, W., She, N., & Ma, Y. (2024). A bibliometric perspective on the occurrence and migration of microplastics in soils amended with sewage sludge. *Water Environment Research*, *96*(6), e11054.

https://doi.org/10.1002/wer.11054

Fu, S.-F., Ding, J.-N., Zhang, Y., Li, Y.-F., Zhu, R., Yuan, X.-Z., & Zou, H. (2018). Exposure to polystyrene nanoplastic leads to inhibition of anaerobic digestion system. *Science of the Total Environment*, *625*, 64–70.

https://doi.org/10.1016/j.scitotenv.2017.12.158

Giannattasio, A., Corpuz, M. V. A., Oliva, G., Iuliano, V., Giaquinto, D., Grassi, A., Zarra, T., Belgiorno, V., Buonerba, A., & Naddeo, V. (2026). Control of Low-Density Microplastics in Wastewater Treatment Plants: The Effects of Process Configuration and Polymer Properties on Removal Efficiency. *ACS ES&T Water*, *6*(4), 2290–2300.

https://doi.org/10.1021/acsestwater.5c01307

Gong, X., Ge, Z., Ma, Z., Li, Y., Huang, D., & Zhang, J. (2023). Effect of different size microplastic particles on the construction of algal-bacterial biofilms and microbial communities. *Journal of Environmental Management*, *343*, 118246.

https://doi.org/10.1016/j.jenvman.2023.118246

Harley-Nyang, D., Memon, F. A., Jones, N., & Galloway, T. (2022). Investigation and analysis of microplastics in sewage sludge and biosolids: A case study from one wastewater treatment works in the UK. *Science of the Total Environment*, *823*, 153735.

https://doi.org/10.1016/j.scitotenv.2022.153735

Huang, S., Zhang, B., Liu, Y., Feng, X., & Shi, W. (2022). Revealing the influencing mechanisms of polystyrene microplastics (MPs) on the performance and stability of the algal-bacterial granular sludge. *Bioresource Technology*, *354*, 127202.

https://doi.org/10.1016/j.biortech.2022.127202

Jachimowicz, P., Jo, Y.-J., & Cydzik-Kwiatkowska, A. (2022). Polyethylene microplastics increase extracellular polymeric substances production in aerobic granular sludge. *Science of the Total Environment*, *851*, 158208.

https://doi.org/10.1016/j.scitotenv.2022.158208

Ji, J., Peng, L., Gao, T., Salama, E.-S., Khan, A., Liu, P., Yun, H., & Li, X. (2023). Microplastics enhanced the toxic effects of sulfamethoxazole on aerobic granular sludge and enriched antibiotic resistance genes. *Chemical Engineering Journal*, *464*, 142783.

https://doi.org/10.1016/j.cej.2023.142783

Jin, Y., Zhao, X., Lema, J. M., Liu, G., & Chen, C. (2026). Microplastic Generation and Persistence of Biodegradable Plastics under Anaerobic Conditions. *Environmental Science & Technology*, *60*(12), 9565–9574.

https://doi.org/10.1021/acs.est.5c18919

Keller, A. S., Jimenez-Martinez, J., & Mitrano, D. M. (2020). Transport of Nano- and Microplastic through Unsaturated Porous Media from Sewage Sludge Application. *Environmental Science & Technology*, *54*(2), 911–920.

https://doi.org/10.1021/acs.est.9b06483

Kendall, M. G. (1975). *Rank Correlation Methods* (4th ed.). Charles Griffin.

Lares, M., Ncibi, M. C., Sillanpää, M., & Sillanpää, M. (2018). Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. *Water Research*, *133*, 236–246.

https://doi.org/10.1016/j.watres.2018.01.049

Lares, M., Ncibi, M. C., Sillanpää, M., & Sillanpää, M. (2019). Intercomparison study on commonly used methods to determine microplastics in wastewater and sludge samples. *Environmental Science and Pollution Research*, *26*(12), 12109–12122.

https://doi.org/10.1007/s11356-019-04584-6

Lessa Belone, M. C., Brosens, D., Kokko, M., & Sarlin, E. (2024). Effects of mesophilic and thermophilic anaerobic digestion of sewage sludge on different polymers: Perspectives on the potential of the treatment to degrade microplastics. *Science of the Total Environment*, *907*, 168014.

https://doi.org/10.1016/j.scitotenv.2023.168014

Li, L., Song, K., Yeerken, S., Geng, S., Liu, D., Dai, Z., Xie, F., Zhou, X., & Wang, Q. (2020). Effect evaluation of microplastics on activated sludge nitrification and denitrification. *Science of the Total Environment*, *707*, 135953.

https://doi.org/10.1016/j.scitotenv.2019.135953

Li, X., Li, M., Mei, Q., Niu, S., Wang, X., Xu, H., Dong, B., Dai, X., & Zhou, J. L. (2021). Aging microplastics in wastewater pipeline networks and treatment processes: Physicochemical characteristics and Cd adsorption. *Science of the Total Environment*, *797*, 148940.

https://doi.org/10.1016/j.scitotenv.2021.148940

Liu, X., Deng, Q., Zheng, Y., Wang, D., & Ni, B.-J. (2022). Microplastics aging in wastewater treatment plants: Focusing on physicochemical characteristics changes and

corresponding environmental risks. *Water Research*, *221*, 118780.

https://doi.org/10.1016/j.watres.2022.118780

Liu, X., Yuan, W., Di, M., Li, Z., & Wang, J. (2019). Transfer and fate of microplastics during the conventional activated sludge process in one wastewater treatment plant of China. *Chemical Engineering Journal*, *362*, 176–182.

https://doi.org/10.1016/j.cej.2019.01.033

Lotka, A. J. (1926). The frequency distribution of scientific productivity. *Journal of the Washington Academy of Sciences*, *16*(12), 317–323. https://www.jstor.org/stable/24529203

Lu, B., Jiang, C., Chen, Z., Li, A., Wang, W., Zhang, S., & Luo, G. (2022). Fate of polylactic acid microplastics during anaerobic digestion of kitchen waste: Insights on property changes, released dissolved organic matters, and biofilm formation. *Science of the Total Environment*, *834*, 155108.

https://doi.org/10.1016/j.scitotenv.2022.155108

Luo, T., Dai, X., Chen, Z., Wu, L., Wei, W., Xu, Q., & Ni, B.-J. (2023). Different microplastics distinctively enriched the antibiotic resistance genes in anaerobic sludge digestion through shifting specific hosts and promoting horizontal gene flow. *Water Research*, *228*, 119356.

https://doi.org/10.1016/j.watres.2022.119356

Luo, T., Dai, X., Wei, W., Xu, Q., & Ni, B.-J. (2023). Microplastics Enhance the Prevalence of Antibiotic Resistance Genes in Anaerobic Sludge Digestion by Enriching Antibiotic-Resistant Bacteria in Surface Biofilm and Facilitating the Vertical and Horizontal Gene Transfer. *Environmental Science & Technology*, *57*(39), 14611–14621.

https://doi.org/10.1021/acs.est.3c02815

Lv, X., Dong, Q., Zuo, Z., Liu, Y., Huang, X., & Wu, W.-M. (2019). Microplastics in a municipal wastewater treatment plant: Fate, dynamic distribution, removal efficiencies, and control strategies. *Journal of Cleaner Production*, *225*, 579–586.

https://doi.org/10.1016/j.jclepro.2019.03.321

Ma, J., Gong, Z., Wang, Z., Liu, H., Chen, G., & Guo, G. (2022). Elucidating degradation properties, microbial community, and mechanism of microplastics in sewage sludge under different terminal electron acceptors conditions. *Bioresource Technology*, *346*, 126624.

https://doi.org/10.1016/j.biortech.2021.126624

Ma, Y., Huang, J., Han, T., Yan, C., Cao, C., & Cao, M. (2021). Comprehensive metagenomic and enzyme activity analysis reveals the negatively influential and potentially toxic mechanism of polystyrene nanoparticles on nitrogen transformation in constructed wetlands. *Water Research*, *202*, 117420.

https://doi.org/10.1016/j.watres.2021.117420

Magni, S., Binelli, A., Pittura, L., Avio, C. G., Della Torre, C., Parenti, C. C., Gorbi, S., & Regoli, F. (2019). The fate of microplastics in an Italian Wastewater Treatment Plant. *Science of the Total Environment*, *652*, 602–610.

https://doi.org/10.1016/j.scitotenv.2018.10.269

Mahon, A. M., O'Connell, B., Healy, M. G., O'Connor, I., Officer, R., Nash, R., & Morrison, L. (2017). Microplastics in Sewage Sludge: Effects of Treatment. *Environmental Science & Technology*, *51*(2), 810–818.

https://doi.org/10.1021/acs.est.6b04048

Maliwan, T., Pungrasmi, W., & Lohwacharin, J. (2021). Effects of microplastic accumulation on floc characteristics and fouling behavior in a membrane bioreactor. *Journal of Hazardous Materials*, *411*, 124991.

https://doi.org/10.1016/j.jhazmat.2020.124991

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245–259.

https://doi.org/10.2307/1907187

Michielssen, M. R., Michielssen, E. R., Ni, J., & Duhaime, M. B. (2016). Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed. *Environmental Science: Water Research & Technology*, *2*(6), 1064–1073.

https://doi.org/10.1039/C6EW00207B

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71.

https://doi.org/10.1136/bmj.n71

Pao, M. L. (1985). Lotka's law: A testing procedure. *Information Processing & Management*, 21(4), 305–320.

https://doi.org/10.1016/0306-4573(85)90055-X

Parashar, N., & Hait, S. (2022). Occurrence and removal of microplastics in a hybrid growth sewage treatment plant from Bihar, India: A preliminary study. *Journal of Cleaner Production*, *376*, 134295.

https://doi.org/10.1016/j.jclepro.2022.134295

Pham, D. N., Clark, L., & Li, M. (2021). Microplastics as hubs enriching antibiotic-resistant bacteria and pathogens in municipal activated sludge. *Journal of Hazardous Materials Letters*, *2*, 100014.

https://doi.org/10.1016/j.hazl.2021.100014

Ragoobur, D., Huerta-Lwanga, E., & Somaroo, G. D. (2022). Reduction of microplastics in sewage sludge by vermicomposting. *Chemical Engineering Journal*, *450*, 138231.

https://doi.org/10.1016/j.cej.2022.138231

Rout, P. R., Mohanty, A., Aastha A., Sharma, A., Miglani, M., Liu, D., & Varjani, S. (2022). Micro- and nanoplastics removal mechanisms in wastewater treatment plants: A review. *Journal of Hazardous Materials Advances*, *6*, 100070.

https://doi.org/10.1016/j.hazadv.2022.100070

Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389.

https://doi.org/10.1080/01621459.1968.10480934

Song, X., Sun, S., Gao, Y., Zhang, W., Zhou, L., B, J. C., Wan, J., Chen, J., Zhou, L., & Yu, G. (2022). Laboratory-scale study of a biodegradable microplastic polylactic acid stabilizing aerobic granular sludge system. *Environmental Pollution*, *306*, 119329.

https://doi.org/10.1016/j.envpol.2022.119329

Talvitie, J., Heinonen, M., Pääkkönen, J.-P., Vahtera, E., Mikola, A., Setälä, O., & Vahala, R. (2015). Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea. *Water Science and Technology*, *72*(9), 1495–1504.

https://doi.org/10.2166/wst.2015.360

Talvitie, J., Mikola, A., Koistinen, A., & Setälä, O. (2017). Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Research*, *123*, 401–407.

https://doi.org/10.1016/j.watres.2017.07.005

Talvitie, J., Mikola, A., Setälä, O., Heinonen, M., & Koistinen, A. (2017). How well is microlitter purified from wastewater? – A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. *Water Research*, *109*, 164–172.

https://doi.org/10.1016/j.watres.2016.11.046

Tang, L., Su, C., Chen, Y., Xian, Y., Hui, X., Ye, Z., Chen, M., Zhu, F., & Zhong, H. (2021). Influence of biodegradable polybutylene succinate and non-biodegradable polyvinyl chloride microplastics on anammox sludge: Performance evaluation, suppression effect and metagenomic analysis. *Journal of Hazardous Materials*, *401*, 123337.

https://doi.org/10.1016/j.jhazmat.2020.123337

Torena, P., Alvarez-Cuenca, M., & Reza, M. (2021). Biodegradation of polyethylene terephthalate microplastics by bacterial communities from activated sludge. *The Canadian Journal of Chemical Engineering*, *99*(S1), 254–262.

https://doi.org/10.1002/cjce.24015

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538.

https://doi.org/10.1007/s11192-009-0146-3

Wang, C., Wei, W., Zhang, Y.-T., Dai, X., & Ni, B.-J. (2022). Different sizes of polystyrene microplastics induced distinct microbial responses of anaerobic granular sludge. *Water Research*, *220*, 118607.

https://doi.org/10.1016/j.watres.2022.118607

Wang, J., Ma, D., Feng, K., Lou, Y., Zhou, H., Liu, B., Xie, G., Ren, N., & Xing, D. (2022). Polystyrene nanoplastics shape microbiome and functional metabolism in anaerobic digestion. *Water Research*, *219*, 118606.

https://doi.org/10.1016/j.watres.2022.118606

Wang, Q., Hernández-Crespo, C., Santoni, M., Van Hulle, S., & Rousseau, D. P. L. (2020). Horizontal subsurface flow constructed wetlands as tertiary treatment: Can they be an efficient barrier for microplastics pollution? *Science of the Total Environment*, *721*, 137785.

https://doi.org/10.1016/j.scitotenv.2020.137785

Wang, Z., Gao, J., Li, D., Dai, H., & Zhao, Y. (2020). Co-occurrence of microplastics and triclosan inhibited nitrification function and enriched antibiotic resistance genes in nitrifying sludge. *Journal of Hazardous Materials*, *399*, 123049.

https://doi.org/10.1016/j.jhazmat.2020.123049

Wei, W., Huang, Q.-S., Sun, J., Dai, X., & Ni, B.-J. (2019). Revealing the Mechanisms of Polyethylene Microplastics Affecting Anaerobic Digestion of Waste Activated Sludge. *Environmental Science & Technology*, *53*(16), 9604–9613.

https://doi.org/10.1021/acs.est.9b02971

Wei, W., Huang, Q.-S., Sun, J., Wang, J.-Y., Wu, S.-L., & Ni, B.-J. (2019). Polyvinyl Chloride Microplastics Affect Methane Production from the Anaerobic Digestion of Waste Activated Sludge through Leaching Toxic Bisphenol-A. *Environmental Science & Technology*, *53*(5), 2509–2517.

https://doi.org/10.1021/acs.est.8b07069

Wei, W., Wang, C., Shi, X., Zhang, Y.-T., Chen, Z., Wu, L., & Ni, B.-J. (2022). Multiple microplastics induced stress on anaerobic granular sludge and an effectively overcoming strategy using hydrochar. *Water Research*, *222*, 118895.

https://doi.org/10.1016/j.watres.2022.118895

Wilkes, R. A., Zhou, N., Carroll, A. L., Aryal, O., Teitel, K. P., Wilson, R. S., Zhang, L., Kapoor, A., Castaneda, E., Guss, A. M., Waldbauer, J. R., & Aristilde, L. (2024). Mechanisms of Polyethylene Terephthalate Pellet Fragmentation into Nanoplastics and Assimilable Carbons by Wastewater *Comamonas*. *Environmental Science & Technology*, *58*(43), 19338–19352.

https://doi.org/10.1021/acs.est.4c06645

Wu, T., Ding, J., Wang, S., Pang, J.-W., Sun, H.-J., Zhong, L., Ren, N.-Q., & Yang, S.-S. (2024). Insight into effect of polyethylene microplastic on nitrogen removal in moving bed biofilm reactor: Focusing on microbial community and species interactions. *Science of the Total Environment*, *932*,

173033.

https://doi.org/10.1016/j.scitotenv.2024.173033

Wu, X., Zhao, X., Chen, R., Liu, P., Liang, W., Wang, J., Teng, M., Wang, X., & Gao, S. (2022). Wastewater treatment plants act as essential sources of microplastic formation in aquatic environments: A critical review. *Water Research*, *221*, 118825.

https://doi.org/10.1016/j.watres.2022.118825

Xu, R.-Z., Cao, J.-S., Ye, T., Wang, S.-N., Luo, J.-Y., Ni, B.-J., & Fang, F. (2022). Automated machine learning-based prediction of microplastics induced impacts on methane production in anaerobic digestion. *Water Research*, *223*, 118975.

https://doi.org/10.1016/j.watres.2022.118975

Yang, X., He, Q., Guo, F., Sun, X., Zhang, J., Chen, M., Vymazal, J., & Chen, Y. (2020). Nanoplastics Disturb Nitrogen Removal in Constructed Wetlands: Responses of Microbes and Macrophytes. *Environmental Science & Technology*, *54*(21), 14007–14016.

https://doi.org/10.1021/acs.est.0c03324

Yang, X., He, Q., Liu, T., Zheng, F., Mei, H., Chen, M., Liu, G., Vymazal, J., & Chen, Y. (2022). Impact of microplastics on the treatment performance of constructed wetlands: Based on substrate characteristics and microbial activities. *Water Research*, *217*, 118430.

https://doi.org/10.1016/j.watres.2022.118430

Yang, X., Zhang, L., Chen, Y., He, Q., Liu, T., Zhang, G., Yuan, L., Peng, H., Wang, H., & Ju, F. (2022). Micro(nano)plastic size and concentration co-differentiate nitrogen transformation, microbiota dynamics, and assembly patterns in constructed wetlands. *Water Research*, *220*, 118636.

https://doi.org/10.1016/j.watres.2022.118636

Yin, Y., Xiao, K., Wang, Y.-F., Cao, J.-M., Dong, J.-P., Zhu, D., & Zhu, Y.-G. (2025). Nanoplastics released from textile washing enrich antibiotic resistance and virulence genes in sewage sludge microbiomes. *Environment International*, *202*, 109611.

https://doi.org/10.1016/j.envint.2025.109611

Yli-Rantala, E., Sarlin, E., & Kokko, M. (2025). Fate of microplastics in a centralized biogas plant treating mainly sewage sludge. *Journal of Environmental Management*, *395*, 127892.

https://doi.org/10.1016/j.jenvman.2025.127892

Zhang, B., Huang, S., Wu, L., Guo, Y., Shi, W., & Lens, P. N. L. (2023). Micro(nano)plastic size and concentration co-differentiate the treatment performance and toxicity mechanism in aerobic granular sludge systems. *Chemical Engineering Journal*, *457*, 141212.

https://doi.org/10.1016/j.cej.2022.141212

Zhang, L., Sun, J., Zhang, Z., Peng, Z., Dai, X., & Ni, B.-J. (2022). Polyethylene terephthalate microplastic fibers increase the release of extracellular antibiotic resistance genes during sewage sludge anaerobic digestion. *Water Research*, *217*, 118426.

https://doi.org/10.1016/j.watres.2022.118426

Zhang, Y.-T., Wei, W., Sun, J., Xu, Q., & Ni, B.-J. (2020). Long-Term Effects of Polyvinyl Chloride Microplastics on Anaerobic Granular Sludge for Recovering Methane from Wastewater. *Environmental Science & Technology*, *54*(15), 9662–9671.

https://doi.org/10.1021/acs.est.0c02433

Zheng, P., Li, Y., Cheng, Y., & Shen, J. (2024). Mechanism Involved in Polyvinyl Chloride Nanoplastics Induced Anaerobic Granular Sludge Disintegration: Microbial Interaction Energy, EPS Molecular Structure, and Metabolism Functions. *Environmental Science & Technology*, *58*(26), 11542–11553.

https://doi.org/10.1021/acs.est.4c01925

Zheng, X., Han, Z., Shao, X., Zhao, Z., Zhang, H., Lin, T., Yang, S., & Zhou, C. (2022). Response of aerobic granular sludge under polyethylene microplastics stress: Physicochemical properties, decontamination performance, and microbial community. *Journal of Environmental Management*, *323*, 116215.

https://doi.org/10.1016/j.jenvman.2022.116215

Zhou, S., Wang, L., Liu, J., Zhang, C., & Liu, X. (2024). Microplastics' toxic effects and influencing factors on microorganisms in biological wastewater treatment units. *Water Science & Technology*, *89*(6), 1539–1553.

https://doi.org/10.2166/wst.2024.040

Ziajahromi, S., Neale, P. A., Telles Silveira, I., Chua, A., & Leusch, F. D. L. (2021). An audit of microplastic abundance throughout three Australian wastewater treatment plants. *Chemosphere*, *263*, 128294.

https://doi.org/10.1016/j.chemosphere.2020.128294