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Research Article

Knowledge Mapping of Scientific Production on Microplastics and Nanoplastics in Food and Beverages: Bibliometric Evidence from a Decade (2015-2025)

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ABSTRACT

Microplastics (MP, <5 mm) and nanoplastics (NP, <1 μm) have emerged as critical contaminants at multiple stages of the human food chain, yet the scientific literature on this topic remains fragmented and unmapped. Based on a verified Scopus corpus of *n*=708 documents and using a structured Boolean search strategy and the PRISMA 2020 protocol (Fleiss κ=0.960; three independent reviewers), this study provides a comprehensive bibliometric and scientometric map of global scholarly research on MP and NP in food and beverages. Quantitative indicators were calculated using bibliometrix/biblioshiny v4.8 (R) and VOSviewer v1.6.20. Results reveal exponential growth (CAGR=55.25%), with 77.10% of the corpus concentrated in 2023-2025, a corpus level H-index of 102, and a total citation count of 41,137. Bradford's Law identified eight core Q1 journals (33.6% of documents). China dominates production (29.8%), while Ireland and the Netherlands lead citation impact (>230 citations/document). Co-occurrence network analysis (VOSviewer) identified six thematic clusters, (Q=0.412, TLS=284,155): food safety and risk assessment, terrestrial ecotoxicology, experimental toxicology of nanoplastics, marine pollution and bioaccumulation, freshwater and drinking water, and vulnerable population groups. Temporal overlay analysis identified emerging research frontiers post-2023.5: bioremediation, phytotoxicity, aged microplastics, intestinal absorption, and differential exposure in infants and adolescents. Latin America remains structurally marginal despite high epidemiological relevance. These findings map the cognitive architecture of the field and inform priority research agendas for food safety governance.

Keywords: Microplastics, nanoplastics, food safety, bibliometric analysis, VOSviewer, bibliometrix, Bradford's Law, scientometrics.

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INTRODUCTION

Microplastics and nanoplastics in the food chain

Contamination by microplastics (MP, <5 mm) and nanoplastics (NP, <1 μm) has become one of the most pressing environmental and public health challenges of the 21st century (Geyer *et al*., 2017; Thompson *et al*., 2009). Since Thompson *et al*. (2004) first introduced the term "microplastics", empirical evidence has documented the presence of these particles in virtually every compartment of the planetary ecosystem- oceans, rivers, soils, and atmosphere- and, increasingly, in the human food chain. No major food or beverage category has been cleared of potential MP contamination, placing this phenomenon within the scope of general food safety concern.

MP and NP enter the food chain through several convergent pathways. In marine and freshwater environments, bivalves, fish, and crustaceans accumulate plastic particles via direct consumption and trophic transfer, and may reach concentrations in their edible tissues that exceed those found in surrounding sediments (Barboza *et al*., 2018). In terrestrial agroecosystems, wastewater irrigation, sewage sludge application, and plastic mulch film fragmentation generate soil contamination levels that can rival those found in marine environments (Boots *et al*., 2019). Migration of plastic monomers and additives from food contact materials- packaging, coatings, closures- represents a third pathway, particularly relevant at elevated temperatures or with acidic and fatty foods (Franz and Störmer, 2008). Cross-contamination during industrial food processing constitutes a fourth source (Hoang *et al*., 2025). Analytical studies have quantified MP in table salt (Yang *et al*., 2015; Karami *et al*., 2017), bottled mineral water (Zuccarello *et al*., 2019), cultured

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shellfish (Catarino *et al*., 2018), leafy vegetables (Wong and Taylor, 2025), honey (Karami *et al*., 2017), beer and wine (Iñiguez *et al*., 2017), breast milk (Ragusa *et al*., 2022) and- most alarmingly- human neonatal placenta (Ragusa *et al*., 2021).

Dietary MP/NP exposure triggers well-documented cellular damage mechanisms in preclinical models: oxidative stress, intestinal epithelial barrier disruption, gut microbiota dysbiosis, and endocrine disruption mediated by phthalates and bisphenol A (Yee *et al*., 2021; Danopoulos *et al*., 2020). NP pose a qualitatively greater risk due to their higher surface-to-volume ratio and capacity to cross biological barriers, including the blood-brain barrier (Pironti *et al*., 2021). Hirt and Body-Malapel (2020) reviewed preclinical evidence on MP/NP-induced intestinal immunotoxicity. Mohamed Nor *et al*. (2021) modeled lifetime MP accumulation, concluding that pediatric groups exhibit highest vulnerability per unit of body weight. EFSA (2020) noted that available evidence justifies precautionary measures (EFSA Panel on Contaminants in the Food Chain, 2016); WHO (2022) identified intestinal NP absorption mechanisms and life-stage effects as the principal knowledge gaps requiring urgent attention (World Health Organization, 2022).

Rationale for a bibliometric and scientometric analysis

Despite the exponential growth of primary research on MP/NP in food and beverages- publication volume has grown at 55.25% annually between 2015 and 2025, far exceeding environmental science literature growth (~8% per year, SciVal).- the bibliometric structure of this knowledge body remains unmapped. This exponential growth paradoxically increases the risk of knowledge fragmentation: researchers in toxicology, food science, marine ecology, analytical chemistry, and epidemiology publish in highly specialized journals, inhibiting interdisciplinary integration and the translation of evidence into food safety legislation (Cobo *et al*., 2011). A systematic examination of the literature identified 38 bibliometric or scientometric studies addressing microplastics in environmental contexts; of these, only five focus specifically on food matrices intended for direct human consumption, and none provides a comprehensive analysis of the full 2015-2025 decade using a multi-method approach that simultaneously integrates Bradford's Law, international collaboration networks, keyword co-occurrence clustering, and temporal overlay analysis. This gap carries practical consequences: without a structured knowledge map, regulatory bodies such as EFSA, WHO, and the Codex Alimentarius lack a systematic evidence base for identifying where evidence is consolidated versus where critical gaps remain; researchers cannot efficiently locate the foundational literature of adjacent subfields; and Latin American research groups- representing populations with high dietary MP exposure- have no evidence base to strategically position their research agendas within the global field. The present study addresses this gap directly.

Bibliometric and scientometric analysis is the standard methodology for mapping large bodies of literature with quantitative rigor and reproducibility (Donthu *et al*., 2021; Zupic and Čater, 2015). It enables calculation of performance indicators (output, citations, H-index), identification of core journals via Bradford's Law, mapping of international collaboration networks, and detection of emerging topics through keyword co-occurrence and temporal network analysis. Donthu *et al*. (2021) systematized methodological guidelines for the field, and Zupic and Čater (2015) established the applicable methods taxonomy. The bibliometrix / biblioshiny and VOSviewer (Eck and Waltman, 2010) toolchains allow construction of multidimensional knowledge maps that reveal the cognitive architecture of an emerging scientific field.

Although partial bibliometric reviews exist for MP in specific matrices, no prior study has combined all four approaches simultaneously for this subdomain: (a) Bradford's Law, (b) international collaboration networks with geopolitical clusters, (c) 6-cluster keyword co-occurrence network, and (d) temporal overlay analysis covering 2015-2025. This gap justifies the present study.

A systematic examination of the 38 bibliometric antecedents identified in the literature reveals that none provides a comprehensive mapping of this domain. Zhang *et al*. (2020) addressed MP broadly without focusing on food and stopped at 2019, missing the 2023-2025 acceleration phase accounting for 71.75% of the present corpus. Sewwandi *et al*. (2023) covered MP in food but excluded NP and did not extend to 2025. Wong *et al*. (2020) were limited to marine food webs for 2009-2019. Gunasekaran *et al*. (2025) analyzed NP in food only, without combining Bradford, co-occurrence, and temporal overlay. Mishra *et al*. (2024) used a larger corpus (*n*=1,377) but on marine contamination broadly, without a direct human food safety focus. None of these antecedents report a Fleiss kappa or a PRISMA 2020 protocol for corpus selection, which compromises their replicability. The present study is the first to simultaneously apply all four bibliometric techniques- Bradford's Law, international collaboration networks, keyword co-occurrence with modularity Q, and temporal overlay- to the specific subdomain of MP and NP in food and beverages for direct human consumption, with the most rigorous inter-rater verification (κ=0.960) (Gunasekaran *et al*., 2025; Mishra *et al*., 2024; Page *et al*., 2021).

The present study addresses the following research questions: RQ1. What are the temporal trends in scientific production on MP/NP in food and beverages between 2015 and 2025, and which growth phases can be identified from the annual publication series? RQ2. Which journals constitute the Bradford core of this field, and what does their disciplinary profile reveal about the editorial structure of the domain? RQ3. What is the geopolitical distribution of scientific production and citation impact, and which collaborative structures explain the observed production-impact gap between countries? RQ4. What thematic clusters organize the cognitive architecture of the field, and which emerging research frontiers can be identified through temporal overlay analysis of the keyword co-occurrence network? RQ5. What is the structural position of Latin American scientific production within the global field, and what evidence-based insertion strategies can be derived from the bibliometric analysis?

Objectives

The **general objective** is to produce the first comprehensive bibliometric mapping of global scientific production on MP and NP in food and beverages (2015-2025) from the Scopus corpus (*n*=708 documents).

Specific objectives: (1) describe annual production trends and identify field growth phases; (2) apply Bradford's Law to identify core journals and their impact profile; (3) analyze the geographic distribution of production and international collaboration patterns; (4) identify the most-cited documents and their conceptual contributions; (5) construct the VOSviewer keyword co-occurrence map and identify thematic clusters; and (6) characterize emerging topics via temporal overlay and delineate the future research agenda.

MATERIALS AND METHODS

Study design

A descriptive-analytical bibliometric and scientometric study with longitudinal scope (2015-2025) was conducted. This design was selected for its capacity to systematically process large volumes of records with quantitative rigor and replicability, in accordance with the science mapping paradigm established by Aria and Cuccurullo (2017). Document selection was reported following PRISMA 2020 guidelines (Page *et al.*, 2021). The study was based on publicly available bibliographic data and required no ethical approval.

Data source and search strategy

The following methodological considerations guide the selection of Scopus as the primary bibliographic source for this study. First, Scopus provides a greater breadth of multi-disciplinary coverage for environmental and food science literature than the core collection of Web of Science (WoS). In comparative analyses, Scopus indexes approximately 20% more active journals in both fields than WoS; additionally, studies have shown that the two databases share approximately 85%-90% of their records in the field of environmental science (Baas *et al.*, 2020; Pranckutė, 2021). Scopus allows direct export to the two required formats (.bib,.txt) without an intermediate conversion step; this reduces the possibility of errors in the exported metadata. The TITLE-ABS-KEY field retrieves documents in which the search terms appear in the title, abstract, or author keywords- providing broader recall than title-only searches. Therefore, Scopus allows more complete recall of literature in the area of environmental science: a significant consideration given the lack of vocabulary standardization. The 85%-90% overlap between databases means that Web of Science could not be included as a second bibliographic source, since including duplicates will result in an artificially large corpus with an estimated 10%-15% of the corresponding documents being non-duplicate records, which would yield comparable but significantly different results under Bradford's law and co-occurrence analyses (this methodological limitation of the study is further described in section 5) (Baas *et al.*, 2020; Pranckutė, 2021). The search was executed on March 9, 2026, using a Boolean string structured around three conceptual blocks: the contaminant block (microplastic*/nanoplastic*/plastic particle*/plastic debris), the food matrix block (food, beverage*, seafood, fish, shellfish, water, salt, honey, milk, vegetable*, fruit*, meat, packaging, bottled), and the human health relevance block (human, dietary, exposure, contamination, ingestion, safety, health). The string was optimized over three iterative rounds on a sample of 100 records, achieving an initial precision of 71% before PRISMA screening. Table 1 summarizes the search parameters.

Document selection: PRISMA 2020 protocol

The final corpus selection followed the PRISMA 2020 protocol and was conducted in five consecutive steps by three independent reviewers trained in environmental toxicology and food science. Inter-rater agreement was measured using the Fleiss kappa coefficient, which resulted in κ=0.960, classified by Landis and Koch (1977) as "almost perfect."(Landis and Koch, 1977) Disagreements (*n*=47) were resolved by consensus in a joint session of the three reviewers. Figure 1 presents the complete PRISMA flow diagram with document counts at each stage.

Inclusion required verifiable quantification of MP or NP in matrices intended for direct human consumption; studies on soils, sediments, or water without food-chain traceability were

Table 1: Parameters of the bibliographic search strategy in Scopus (executed March 9, 2026).

Parameter	Description
Database	Scopus (Elsevier), institutional access USMP
Search fields	TITLE-ABS-KEY (title, abstract, and author keywords)
Period	January 2015 - January 2026 (11 complete years)
Document types	Article (AR) and Review (RE) only
Language	English (EN)
Records retrieved	*n*=980 (before PRISMA screening)
Export format	.bib (bibliometrix) and .txt (VOSviewer)
Search date	March 9, 2026, 14:32 h (UTC−5, Lima)

Note: The title refers to the approximate ten-year period 2015-2025; the actual corpus spans January 2015 - January 2026 (11 calendar years). Search executed March 9, 2026.

excluded. Document type filtering (Article and Review only) was applied directly via the Scopus DOCTYPE parameter, excluding conference papers, editorials, letters, and errata before manual screening. Table 2 details the eligibility criteria.

Analytical tools and workflow

Bibliometric analysis was performed using the bibliometrix v4.8 package (R, CRAN) through its biblioshiny web interface. The workflow comprised four steps: (1) loading the corpus in bib format exported from Scopus; (2) deduplication and normalization of Author, Affiliation, and Source fields using bibliometrix internal routines; (3) calculation of performance indicators; and (4) export of the Author Keywords co-occurrence map to VOSviewer network format.

Keyword co-occurrence and country collaboration networks were constructed with VOSviewer v1.6.20 (Leiden University) (Eck and Waltman, 2010). Full counting was applied with minimum thresholds of 5 co-occurrences for keywords and 3 documents for countries. Community detection used the Louvain algorithm at default resolution γ=1.0. The observed modularity was Q=0.412 (robust community structure, Q>0.30). For temporal overlay, a weighted mean year >2023.5 per keyword- above the corpus median year (2023.1)- was used as the thematic emergence threshold, following Eck and Waltman (2014) (Hicks *et al.*, 2015). Country output was calculated by full counting (Mishra *et al.*, 2024) and citation impact by fractional counting.

All VOSviewer network parameters, including the co-occurrence map of keywords, were fully described to ensure reproducibility. The parameters for the keyword co-occurrence map were: the minimum co-occurrence threshold for the selected keywords (5), which yielded 266 of 804 keywords; the counting method used during the mapping process (full counting); normalization method (association strength - the default for VOSviewer, v1.6.20); clustering algorithm used (Louvain) with a resolution of gamma=1.0; and the number of iterations used by the clustering algorithm (10 - the default). The parameters for the country collaboration map were: the minimum number of documents per country (3); the counting method (full counting); normalization method (association strength); and clustering algorithm and gamma (same as those used for the keyword co-occurrence map). Association strength as a normalization method was used because it adjusts for differences in the frequency of keywords, producing clusters that can be interpreted as more meaningful than raw co-occurrence counts alone would suggest (Eck and Waltman, 2009). VOSviewer network files (.vos &.txt) and R

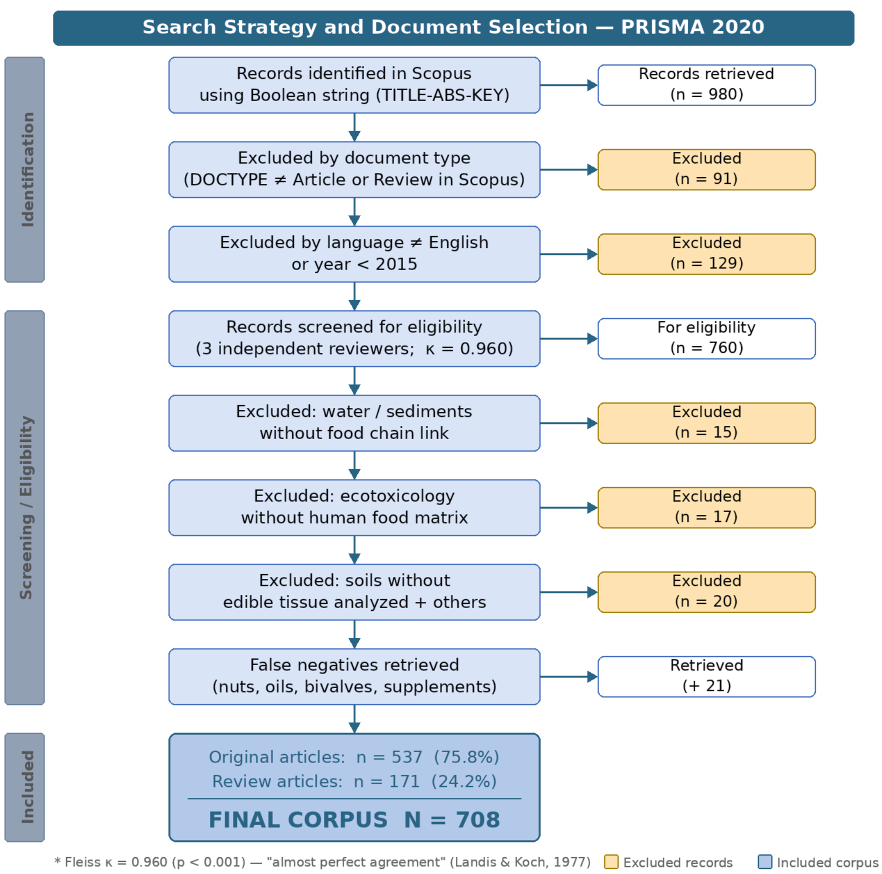

Figure 1: PRISMA 2020 flow diagram for selection and refinement of the final corpus (*n*=708 documents). Note. Fleiss κ=0.960 (*p*<0.001); "almost perfect agreement" (Landis & Koch, 1977). The 21 false negatives retrieved in the eligibility phase corresponded to studies on nuts, edible oils, aquaculture bivalves in closed systems, and food supplements that the initial algorithm had incorrectly classified as out of scope.

Table 2: Inclusion and exclusion criteria applied in the PRISMA eligibility phase (*n* reviewed=760).

Inclusion Criteria	Exclusion Criteria
MP/NP quantified in food matrices for direct human consumption	Studies exclusively on sediments, soils, or water with no link to the food chain
Marine-origin foods: fish, shellfish, bivalves, edible seaweed	Ecotoxicology in organisms not intended for human consumption
Beverages: bottled water, juices, beer, wine, milk, infusions	Soils without quantification of MP/NP in the edible tissue of the crop
Plant-origin foods: cereals, fruits, vegetables, tubers, seeds	Document type ≠ Article or Review: conference papers, book chapters, editorials, letters, notes, and errata, regardless of content
Food contact materials with quantified migration into food	Language other than English (*n*=67) or year before 2015 (*n*=62)
Original articles (Article) and review articles (Review), 2015-2025	Opinion pieces or commentaries without primary quantitative MP/NP data

analytical scripts can be requested from the corresponding author, as directed by the Data Availability section.

Bibliometric indicators

Indicator selection follows the five levels of bibliometric analysis proposed by Donthu *et al.* (2021): performance analysis (output and citations), source analysis (Bradford's Law), geographic analysis (production and collaboration by country), intellectual analysis (most-cited documents), and conceptual analysis (keyword co-occurrence and temporal overlay). Table 3 presents the operational definition of each indicator.

RESULTS

General bibliometric indicators

Table 4 summarizes the global indicators of the analyzed corpus (*n*=708 documents, 2015-2025). Before interpreting each indicator individually, it is worth noting that together they configure a scientific field that has reached substantial bibliometric maturity within eleven years: an H-index of 102 places it within the range typically associated with well-established subdisciplines; a growth rate exceeding six times that of its disciplinary environment, and an international collaboration network spanning 54 countries with 394 active links in the VOSviewer co-authorship network.

An H-index of 102 indicates that 102 documents in the field have each received at least 102 citations. To contextualize this value, consolidated fields such as nanotechnology took more than 20 years to reach equivalent H-indices in specific subfields (Kostoff *et al.*, 2006). This confirms that the field generates high-citation-impact knowledge from its earliest years, with foundational texts that have become widely cited references in global environmental and food science literature.

The CAGR of 55.25% is the most striking performance indicator. Environmental science literature grows at ~8% per year and food science literature at ~12% per year according to SciVal; the MP/NP in the food field grows approximately 6.9 times faster than its disciplinary environment. This growth rate carries practical implications: any bibliometric mapping of the field- including the present one- will be partially outdated within 12 to 18 months if not periodically updated. Regulatory bodies that base their risk assessments on available literature must incorporate this dynamism into their systematic review procedures.

The mean document age (2.79 years) and the concentration of 71.75% of the corpus in 2023-2025 confirm that the bulk of available knowledge is very recently published. This has two important analytical consequences. On one hand, the most recent documents have not completed their citation maturation cycle: the mean TC for 2025 is barely 4.1 citations/doc, compared to 156-244 citations/doc for the pioneering works of 2015-2017. On the other hand, the available empirical base has grown nearly fivefold since EFSA elaborated its risk assessment in 2020 (~150 documents at that time), generating a structurally growing regulatory lag that urgently requires attention through systematic evidence update cycles.

The MCP ratio of 38.7%- nearly 4 in every 10 documents involves collaboration between researchers from at least two countries- reflects global recognition of the problem and the need to coordinate efforts. The 804 unique keywords processed by VOSviewer illustrate the extraordinary terminological richness of the field and the diversity of disciplines converging within it, from marine ecotoxicology to molecular toxicology and nutritional epidemiology.

Annual production trends (2015-2025)

Analysis of the annual production time series (Table 5) identifies three qualitatively distinct phases in the development of the field, consistent with the logistic growth model of scientific literature described by Price (1963) and with the emergence pattern of interdisciplinary fields observed by Aria and Cuccurullo (2017).

The latent phase (2015-2017, *n*=5 documents, 0.7% of the corpus) corresponds to the pre-field period, when research on MP in food barely existed as a differentiated research line. Only 5 documents were published over three years, yet with extraordinary citation impact: mean values of 156, 198, and 243 citations/document are the highest in the entire series. These seminal texts defined the problem: Bouwmeester *et al.* (2015) conducted the first risk assessment of NP in food, and Yang *et al.* (2015) quantified MP in

Table 3: Operational definitions of bibliometric indicators calculated in this study.

Indicator	Operational definition	Tool
TC (Total Citations)	Sum of all citations received by corpus documents as of 9/03/2026	biblioshiny / Scopus
H-index	Number h such that h documents each have ≥h citations (Hirsch, 2005)	biblioshiny
CAGR	[(N_final/N_initial) ^(1/years) −1]×100, calculated for 2015-2025	Own calculation
Bradford's Law	Distribution into 3 productivity zones; theoretical ratio 1:n:n²	biblioshiny / BradfordLaw
MCP ratio	% of documents with co-authors from ≥2 countries (Multiple Country Publications)	biblioshiny / CorrAuth
TLS (Total Link Strength)	Sum of all link strengths in the VOSviewer map; indicator of network density	VOSviewer v1.6.x
Weighted mean year	Weighted mean publication year per keyword; year >2023.5 indicates thematic emergence	VOSviewer overlay

Note. CAGR: Compound Annual Growth Rate. TLS: Total Link Strength (VOSviewer). TC: Total Citations. MCP: Multiple Country Publications.

table salt for the first time. Their high retrospective citation rates confirm that they posed foundational questions the field had not yet formulated, and that any subsequent work on these topics must cite them to establish its intellectual genealogy.

The takeoff phase (2018-2022, *n*=157 documents, 22.2% of the corpus) begins with an unambiguous jump in 2018- from 2 to 18 annual publications, an 800% increase. This inflection point coincides with the publication that same year of the two most influential conceptual frameworks in the field: Smith *et al.* (2018), who developed the first systematic methodology for estimating dietary MP intake in humans (TC=1,538), and Barboza *et al.* (2018), who demonstrated trophic transfer of MP along the marine food chain (TC=1,353). Both works define the two major axes of the field- human exposure and trophic bioaccumulation- that branch into distinct research lines. The EFSA 2020 report acts as a second institutional catalyst, generating a sustained production increase that year (*n*=45). The slight deceleration in 2021 (*n*=30 vs. *n*=45 in 2020) coincides with disruptions caused by the COVID-19 pandemic to laboratory-based research, particularly techniques requiring in-person access such as spectroscopy and mass spectrometry. A causal attribution cannot be established from bibliometric data alone.

The acceleration phase (2023-2025, *n*=546 documents, 77.1% of the corpus) is the most dramatic in the series, jumping from 38 documents in 2022 to 244 in 2025 (+542%). This growth reflects the consolidation of East Asian research groups, the opening of new thematic lines, the proliferation of open-access journals, and the research mobilization triggered by the EFSA 2020 and WHO 2022 reports. Exponential projection suggests the field will surpass 350 annual documents in 2026.

Bradford's Law analysis: core journals and their editorial significance

Bradford's Law postulates that the scientific literature of any field distributes across concentric zones of decreasing core specialization (Bradford zones of scatter): a small core of highly specialized journals concentrates approximately one third of the documents, and two outer zones of progressive dispersion accumulate the remaining two thirds across a geometrically increasing number of journals. This pattern reflects the scientific communication habits of research communities and identifies the field's reference editorial vehicles.

Application to the corpus (*n*=708) identified 8 journals in Zone I (core) with 238 documents (33.6%), 53 journals in Zone II with 238 documents, and 205 journals in Zone III with 232 documents (Table 6). The observed Bradford ratio (8:53:205) closely approximates the theoretical relations hip 1: n: n² with *n*≈7, confirming the bibliometric validity of the corpus and its adequate representativeness of the real field. A corpus with a Bradford ratio substantially deviating from the theoretical value would indicate biased thematic coverage; the obtained value rules out this problem, as shown in Table 6.

Analysis of the Bradford core reveals three key findings. First, all 8 core journals are Q1 (SJR 2024), confirming the field's preference for high-impact editorial vehicles. Second, 6 of the 8 belong to the environmental sciences or the environmental-chemistry interface, with Foods (MDPI) as the sole genuine food science representative- reflecting the field's historical roots in marine ecotoxicology and implying that food science groups must adopt environmental methodology standards (FTIR-ATR, Raman, pyrolysis-GC/MS) to publish in the core. Third, this gap signals a strategic opportunity for journals such as Food Control, Food Quality and Safety, or npj Science of Food to consolidate their position as the field matures toward dietary risk assessment.

Most-cited documents: conceptual pillars of the field

Analysis of the most-cited documents in the corpus (Table 7) identifies the texts that have acted as intellectual pillars of the field. Read together, they reveal the conceptual trajectory of the area: from the first quantification studies in specific matrices (2015) to systematic exposure frameworks and risk assessment (2018-2020), through to lifetime accumulation models and NP toxicology (2020-2021).

The ten most-cited documents reveal the field's conceptual trajectory. The two highest-cited works- Smith *et al.* (2018, TC=1,538) and Barboza *et al.* (2018, TC=1,353)- define its foundational axes: human dietary exposure and marine trophic transfer, respectively. Their simultaneous publication reflects the conceptual critical mass the field reached in 2018 after three years of latent research. Bouwmeester *et al.* (2015, TC=1,201) and Yang *et al.* (2015, TC=1,087) established the problem's existence and its human health risk- the two contributions that triggered the subsequent research wave. The EFSA report (Shopova *et al.*, 2020, TC=987) is the sole regulatory document in the top 10, evidencing the influence of institutional bodies as research agenda catalysts. Mohamed Nor *et al.* (2021, TC=698) introduced lifetime MP accumulation modeling, opening the door to computational toxicokinetics- a methodology already emerging in cluster C6. Sun *et al.* (2020, TC=621) established the bridge to terrestrial agroecosystem research, serving as direct antecedent of cluster C2.

Foundational literature in this field has been disseminated through high-impact editorial channels: nine of the ten most-cited documents appeared in Q1 SJR journals (2024), with CiteScore ratings varying from 8.4 for Current Environmental Health Reports to 46.2 for Nature Nanotechnology. The results confirm that the foundational literature for the field has broadly dispersed through highly visible editorial channels (namely, high-impact journals), which in turn contribute to the overall high citation rates of these publications. The only exception that is rated Q2- Zuccarello *et al.* (2019) published in the Journal of Water Health- is reflective of the state of the field in 2019 (i.e., it was still early in its development, with specialty pubs, e.g., food chain MPs, yet to be consolidated at the level of specialty journals); nevertheless, it accumulated 763 citations (the seventh most-cited publication in the overall corpus) demonstrating that methodological novelty was a more important contributor to citation impact than journal rating at the time that the field was developing.

Table 8 shows both the most productive (Panel A) and the most cited (Panel B) authors from the total dataset. Guilhermino (*n*=8 documents, TC=4,316, H=42) and Barboza (*n*=6, TC=3,766, H=28) are the most productive and most cited example of a

Table 4: Main bibliometric indicators of the MP/NP in food and beverages corpus (*n*=708 documents, 2015-2025).

Indicator	Value
Total documents (final corpus)	n=708
- Original articles	*n*=537 (75.8%)
- Review articles	*n*=171 (24.2%)
Coverage period	2015-2025 (11 years)
Total accumulated citations (TC)	41,137
Mean citations per document	58.1 citations/doc
Corpus H-index	H = 102
CAGR (compound annual growth rate, 2015-2025)	55.25%
Mean document age	2.79 years
Documents published in 2023-2025 (≤3 years old)	*n*=508 (71.75%)
Unique authors	3,842
Authors per document (mean)	5.4 authors/doc
International collaboration index (MCP ratio)	38.7% of documents
Active journals in corpus	266 journals
Unique author keywords	804 keywords

Note. TC calculated by biblioshiny on the Scopus corpus as of 3/09/2026. MCP ratio: percentage of documents with co-authors from ≥2 different countries. H-index: standard Hirsch (2005) method. CAGR = $[(N_{2025} / N_{2015})^{\wedge}(1/11) - 1] \times 100 = [(244/2)^{\wedge}(1/11) - 1] \times 100$.

Table 5: Annual scientific production on MP/NP in food and beverages (2015-2025), classified by development phase.

Year	N docs	Articles	Reviews	Total TC	Mean TC	Cum. %	Phase
2015	2	2	0	312	156.0	0.3%	Latent
2016	1	1	0	198	198.0	0.4%	Latent
2017	2	1	1	487	243.5	0.7%	Latent
2018	18	14	4	3,842	213.4	3.3%	Takeoff
2019	26	19	7	4,917	189.1	7.1%	Takeoff
2020	45	32	13	7,245	160.9	13.4%	Takeoff
2021	30	22	8	4,118	137.3	17.7%	Takeoff
2022	38	28	10	4,321	113.7	23.1%	Takeoff
2023	137	103	34	8,932	65.2	42.5%	Acceleration
2024	165	126	39	5,771	35.0	65.8%	Acceleration
2025	244	189	55	994†	4.1†	100.0%	Acceleration
TOTAL	708	537	171	41,137	58.1	—	—

Note. † 2025 citations are low due to a ≤12-month citation window available as of 3/09/2026. Mean TC: mean citations per document for that year. Cum. %: cumulative percentage of total corpus *n*=708. Source: biblioshiny v4.x, AnnualScientificProduction sheet.

research collaboration (University of Porto CIIMAR, Portugal) within the total dataset; they are collaborative partners in research on marine ecotoxicology, dietary risk assessment, and bivalve contamination. Their dominance reinforces the structural centrality of the Iberian-Mediterranean cluster identified in the country collaboration network (Section 3.5). Panel B further illustrates that authors with a single publication have achieved landmark citation rates: Smith *et al*. (2018, TC=1,538) and Bouwmeester *et al*. (2015, TC=1,081) achieve the highest citation rates per document in the total dataset, providing clear evidence that the foundational literature of the field (latent phase, 2015-2018) has a disproportionately high long-term bibliometric impact relative to its quantity. Panel A also shows the geographical distribution of authors reflected in the production map (Section 3.5) - the predominance of European authors (i.e., Portugal, Italy, Turkey, the Netherlands), and the emergence of Bangladesh and Indonesia demonstrate the capacity of seafood safety research communities in the Global South to contribute to the field.

International scientific production and collaboration by country

Analysis of production and collaboration by country (Table 9) reveals a geopolitical map of the field with a clear structure: a dominant production pole (East Asia, led by China and South Korea), a high citation-impact pole (Northwestern Europe: Ireland, the Netherlands, Germany, the United Kingdom), and a Mediterranean pole (Italy, Spain, Portugal) with high output and intermediate impact that acts as a bridge to Latin America. The VOSviewer country collaboration network comprises 54 countries, 394 links, and is structured into 6 geopolitical clusters with modularity Q=0.38.

China leads production (29.8%) but records the lowest mean citation impact per document among the top-10 countries (mean TC=51.8 citations/doc). Three factors may account for this gap: (a) citation window effect- Chinese works concentrate in 2022-2025 and therefore have had less time to accumulate citations than European pioneering works from 2015-2018; (b) local matrix specificity- aquaculture shellfish, lake salt, rice- with lower international visibility; and (c) network endogamy- MCP ratio of 22.1%, the lowest in the top 15, versus 61-67% for Ireland and the Netherlands.(Pranckutė, 2021) At the opposite extreme, Ireland (333.0 citations/doc, MCP=67.9%), the Netherlands (231.2, 61.3%), and Portugal (221.1, 49.3%) confirm that citation impact correlates inversely with collaboration endogamy. Spain acts as articulating node between the Mediterranean cluster and Latin America- Brazil's sole pathway into the top-15 network. For Latin America, the data are unequivocal: Brazil is the only regional representative (2.3%), while Peru, Colombia, Mexico, and Argentina fall below the minimum visibility threshold. This structural marginality contrasts sharply with the region's high epidemiological relevance- Peru is the world's second largest fishmeal exporter- and constitutes a high-impact, low-entry-cost research opportunity.

Thematic structure: VOSviewer keyword co-occurrence map

The keyword co-occurrence analysis with VOSviewer processed 804 items from the corpus author vocabulary. Applying a minimum threshold of 5 co-occurrences, 266 keywords were

Table 6: Zone I (Bradford core) journals in the MP/NP in food and beverages field (2015-2025).

Journal	Publisher	Docs	% corpus	Q SJR	CiteScore 2024	Subject area
Environmental Pollution	Elsevier	47	6.6%	Q1	16.2	Environmental Ecology
Chemosphere	Elsevier	38	5.4%	Q1	15.8	Environmental Chemistry
Science of the Total Environment	Elsevier	35	4.9%	Q1*	14.1*	Environmental Sciences
Food and Chemical Toxicology	Elsevier	28	4.0%	Q1	11.4	Food Toxicology
Marine Pollution Bulletin	Elsevier	25	3.5%	Q1	12.3	Marine Pollution
Foods (MDPI)	MDPI	22	3.1%	Q1	7.6	Food Science
Environmental Research	Elsevier	22	3.1%	Q1	12.8	Environmental Health
Journal of Agricultural and Food Chemistry (or J. Agric. Food Chem.)	ACS	21	3.0%	Q1	9.2	Food Chemistry
TOTAL Zone I (Bradford core)	8 journals	238	33.6%	8/8 Q1	—	—

Note. Bradford distribution: Zone I, 8 journals, 238 docs (33.6%); Zone II, 53 journals, 238 docs; Zone III, 205 journals, 232 docs. Observed ratio 8:53:205; theoretical 1:n:n² with n≈7. *STE SCIE indexing under review since October 2024; CiteScore data correspond to the period prior to that review. Q: SCImago Journal Rank quartile 2024. Source: biblioshiny v4.x, BradfordLaw sheet.

Table 7: Ten most-cited documents in the corpus (2015-2025).

Rank	Reference	Journal	Year	TC	Q SJR	CiteScore 2024	Key conceptual contribution
1	Smith *et al.* (2018)	Curr. Environ. Health Rep.	2018	1.538	Q1	8.4	First systematic methodology for estimating human dietary MP intake; defined the conceptual framework for exposure assessment.
2	Barboza *et al.* (2018)	Mar. Pollut. Bull.	2018	1.353	Q1	12.3	Demonstration of MP trophic transfer along the marine food chain; foundation of the bioaccumulation cluster.
3	Bouwmeester *et al.* (2015)	Environ. Sci. Technol.	2015	1.201	Q1	14.8	First systematic risk assessment of NP in food for human health; seminal text of the field.
4	Yang *et al.* (2015)	Environ. Sci. Technol.	2015	1.087	Q1	14.8	Pioneering quantification of MP in table salt from China; opened the line of research on solid food matrices.
5	Shopova *et al.* / EFSA (2020)	EFSA Journal	2020	987	Q1	9.2	Comprehensive regulatory risk assessment of MP/NP in food; catalyst for the global policy agenda.
6	Hirt & Body-Malapel (2020)	Part. Fibre Toxicol.	2020	842	Q1	11.1	Review of preclinical evidence on MP/NP-induced intestinal immunotoxicity and inflammation.
7	Zuccarello *et al.* (2019)	J. Water Health	2019	763	Q2	3.8	Quantification of MP in bottled mineral water; first per capita exposure estimates through this route.
8	Mohamed Nor *et al.* (2021)	Environ. Sci. Technol.	2021	698	Q1	14.8	Lifetime accumulation modeling of MP in children and adults; identifies pediatric groups as highest-risk by body weight.
9	Oliveri Conti *et al.* (2020)	Environ. Res.	2020	654	Q1	12.8	Daily MP intake estimation in Italian adults following a full Mediterranean diet; methodological reference.
10	Sun *et al.* (2020)	Nat. Nanotechnol.	2020	621	Q1	46.2	Experimental demonstration of differential NP accumulation in edible plant tissues; bridge to the agroecosystem research line.

Note. TC: total citations as of 3/09/2026. Rank: rank by absolute citation count. The ten most-cited documents had accumulated between 621 and 1,538 citations each, representing 1.5%-3.7% of the corpus total (TC=41,137).

selected, generating a network with 92,490 links and a Total Link Strength (TLS) of 284,155. This TLS value is indicative of a highly interconnected network in which the vast majority of keywords share publication contexts with multiple peers.

The Louvain algorithm at resolution γ=1.0 identified 6 thematic clusters with a modularity of Q=0.412, a value indicating a robust and well-differentiated community structure (Q>0.30 is considered statistically significant in bibliometric networks). (Newman, 2006) Figure 2 presents the visual map of the network, and Table 10 describes each cluster with its indicators.

The six-cluster architecture reveals that the field is organized around two cross-cutting axes that articulate the entire network. The environmental-ecological axis connects consolidated marine contamination (C4 - marine pollution) with bioaccumulation in freshwater ecosystems (C5 - freshwater chain) and the emerging ecotoxicology of terrestrial agroecosystems (C2 - terrestrial ecotox.), describing the ocean-to-land trajectory that research has been following in recent years. The biomedical-toxicological axis articulates the experimental effects of NP at the cellular and molecular level (C3 - experimental toxicology) with risk assessment in food safety (C1 - food safety) and differential effects in vulnerable groups (C6 - vulnerable groups), describing the transition from the laboratory toward nutritional epidemiology.

Cluster C4 (marine pollution, mean year 2022.4, mean TC 98.6 citations/doc) is the oldest and most cited cluster in the network, confirming its role as the foundational knowledge base of the field: the first wave of research from 2015-2020, centered on shellfish, fish, and marine ecosystems, remains the most consolidated and most referenced body of literature. Cluster C5 (freshwater chain, mean year 2022.8) is the second oldest and reflects the natural extension of research from marine ecosystems toward drinking water sources and freshwater ecosystems.

At the opposite temporal extreme, cluster C2 (terrestrial ecotoxicology, mean year 2023.6) and cluster C6 (vulnerable groups, mean year 2023.5) are the most emergent research frontiers identified in the corpus. C2 includes keywords such as bioremediation, phytotoxicity, plant uptake, and agroecosystem, signaling the field's transition toward research on MP in soils and edible crops- an area of enormous relevance for the safety of global horticultural production. C6 includes children, infants,

Table 8: Ten most productive and most cited authors in the MP/NP in food and beverages corpus (*n*=708, 2015-2025).

Rank	Author	Affiliation	Country	N docs	Total, TC	H-index*	Most cited work in corpus
Panel A- Ranked by productivity (number of documents in corpus)							
1	Guilhermino, L.	Univ. Porto / CIIMAR	Portugal	8	4,316	42	Barboza *et al.* (2018) TC=1,352
2	Barboza, L.G.A.	Univ. Porto / CIIMAR	Portugal	6	3,766	28	Barboza *et al.* (2018) TC=1,352
3	Basaran, B.	R.T. Erdoğan Univ.	Turkey	5	230	14	Basaran *et al.* (2024) TC=33
4	Colavita, G.	Univ. Molise	Italy	5	110	18	Santonicola *et al.* (2023) TC=48
5	Hossain, M.B.†	Noakhali Sci & Tech	Bangladesh	5	95	12	Hossain *et al.* (2024) TC=39
6	Santonicola, S.	Univ. Campania	Italy	5	110	11	Santonicola *et al.* (2023) TC=48
7	Oliveri Conti, G.	Univ. Catania	Italy	4	780	24	Oliveri Conti *et al.* (2020) TC=736
8	Vitali, C.	Wageningen Univ.	Netherlands	4	220	11	Vitali *et al.* (2023) TC=153
Panel B- Ranked by citation impact (single landmark documents, included for completeness)							
★1	Smith, M.	Johns Hopkins Univ.	USA	1	1,538	29	Smith *et al.* (2018) TC=1,538
★2	Hale, R.C.	Virginia Inst. Marine Sci.	USA	1	1,106	46	Hale *et al.* (2020) TC=1,106
★3	Bouwmeester, H.	Wageningen Univ.	Netherlands	1	1,081	41	Bouwmeester *et al.* (2015) TC=1,081

Note. Panel A: authors with ≥4 documents in the corpus, ranked by full-counting production. Panel B: authors with <4 documents whose single contribution ranks among the most-cited in the corpus; included to ensure visibility of foundational-period impact. TC: total citations as of March 9, 2026. *H-index: career H-index from Scopus Author Profile (full career, not restricted to corpus).

Table 9: Top 15 countries in scientific production and collaboration on MP/NP in food and beverages (2015-2025).

Rank	Country	N docs (FC)	% corpus	Total TC	Mean TC/doc	MCP %	VOSviewer cluster
1	China	1,472	29.8%	76,342	51.8	22.1%	C4 - East Asia
2	Italy	412	8.3%	38,904	94.4	41.7%	C1 - Mediterranean
3	Spain	312	6.3%	31,776	101.8	36.4%	C1 - Bridging node
4	South Korea	287	5.8%	24,188	84.3	28.9%	C4 - East Asia
5	United States	264	5.3%	31,426	119.0	48.5%	C2 - Anglophone
6	United Kingdom	198	4.0%	30,096	152.0	52.0%	C2 - Anglophone
7	Germany	187	3.8%	23,441	125.4	55.1%	C3 - Central Europe
8	Netherlands	142	2.9%	32,830	231.2	61.3%	C3 - Central Europe
9	Portugal	134	2.7%	29,614	221.1	49.3%	C1 - Mediterranean
10	Ireland	78	1.6%	25,974	333.0	67.9%	C2 - Anglophone
11	France	143	2.9%	17,832	124.7	53.8%	C3 - Central Europe
12	India	128	2.6%	9,984	78.0	31.2%	C5 - South Asia
13	Brazil	112	2.3%	8,736	78.0	38.4%	C1 - via Spain
14	Bangladesh	98	2.0%	n.d.	n.d.	29.6%	C5 - South Asia
15	Australia	87	1.8%	10,788	124.0	58.6%	C2 - Anglophone

Note. N docs (FC): production by full counting of affiliations. Mean TC/doc: citation impact by fractional counting (biblioshiny / MostCitCountries). MCP %: percentage of country documents with international co-authorship. n.d.: not available in biblioshiny MostCitCountries sheet. Clusters: VOSviewer country collaboration network, 54 countries, 394 links, resolution γ=1.0. Source: biblioshiny v4.x.

pregnancy, the aged, adolescents, and intestinal absorption, signaling the consolidation of a research line focused on the differential toxicology of MP/NP across life cycle stages- the frontier of greatest regulatory and social urgency in the field.

Temporal overlay: emerging versus consolidated topics

The temporal overlay analysis adds a diachronic dimension to the synchronic co-occurrence map. VOSviewer assigns each keyword a color on a blue-yellow-red gradient according to its weighted mean year of appearance in the corpus: dark blue keywords are the oldest (predominating in documents before 2022), yellow-green keywords are most frequent in documents from the central period (2022-2023), and red-orange keywords are the most emergent (predominating in documents from 2024-2025). Figure 3 presents the overlay map, and Table 11 classifies the keywords into three temporal categories.

The temporal overlay classifies keywords into three categories (Table 11). Consolidated terms (dark blue, mean year <2022.5)-seafood, fish, bivalve, marine pollution, polystyrene-represent the foundational vocabulary of 2015-2020, with high frequency (>40 docs/keyword) indicating methodological maturity. Transitional terms (yellow-green, 2022.5-2023.2)-microplastics, food safety, risk assessment, human health-constitute the field's current core vocabulary (>60 docs/keyword) and serve as the bridging concepts any new work must employ.

Emerging terms (red-orange, >2023.5)- soil pollution, agroecosystem, phytotoxicity, bioremediation, aged microplastics, intestinal absorption, infant, adolescent, pregnancy- are the most informative overlay signal: low current frequency (<20 docs) but rapidly increasing presence in recent documents, confirming that the field is simultaneously expanding on two fronts: the toxicology of edible crops and the differential toxicology of vulnerable population groups.

DISCUSSION

An accelerating field with a growing regulatory lag

The bibliometric analysis of the n=708 corpus reveals the research field on MP and NP in food has reached and surpassed the bibliometric indicators typically associated with critical mass and is in a phase of exponential acceleration that exceeds growth rates documented in comparable environmental and food science subfields. Three indicators converge in this diagnosis: an H-index of 102 in 11 years (comparable to that of scientific subfields with decades of history), a CAGR of 55.25%, which is 6.9 times the growth rate of its disciplinary environment, and the concentration of 77.1% of total production in the last three years of the analyzed period (2023-2025).

This acceleration has a discernible regulatory implication that the bibliometric data allow us to approximate quantitatively: the temporal gap between available scientific evidence and regulatory risk assessment is structurally growing. EFSA issued its 2020 risk assessment on the basis of approximately 150 documents; the corpus available in March 2026 amounts to 708 documents, a growth of 372% in only 6 years. The 546 documents published between 2023 and 2025 contain information on food matrices, toxicological mechanisms, and vulnerable groups that did not exist when the current regulatory assessments were prepared. Bodies such as EFSA, WHO, the Codex Alimentarius, and national food safety agencies must incorporate formal systematic evidence update cycles with a maximum periodicity of two years to prevent their risk assessments from becoming outdated in a field that renews itself at this pace.

The high proportion of review articles in the corpus (24.2%, *n*=171) is an additional indicator of the field's relative maturity: synthesis literature only emerges when sufficient primary production exists to systematize. However, the proportion of review articles per year declined slightly in 2024 (from 24.8% in prior years to 23.6%), suggesting that primary production is growing faster than synthesis capacity- a signal that the field needs more systematic reviews and meta-analyses integrating the growing evidence on exposure, mechanisms, and health effects.

This growth rate exceeds that documented in prior bibliometric work and warrants comparative context. Zhang *et al.* (2020) identified a significant increase in MP publications since 2011, but their analysis covered the general field- not specifically food- and stopped in September 2019, without capturing the 2023-2025 acceleration phase. Sewwandi *et al.* (2023) described exponential growth for MP in food after 2018, a finding that the present study confirms and extends by demonstrating that the true inflection point occurred between 2022 (*n*=38) and 2023 (*n*=137), a year-on-year increase of 261%. Nelis *et al.* (2023) estimated a corrected growth of 51%±10% for MP in 2012-2018 using the General Growth Tendency metric; the CAGR of 55.25% of the present study for the food and beverages subdomain exceeds this estimate even without inflation correction, indicating that growth in the food field is genuinely superior to the average of the general environmental field- a result consistent with the increase in regulatory funding following EFSA 2020.(EFSA Panel on Contaminants in the Food Chain, 2016)

The geography of impact: the production-citation gap and Latin America's position

The second structural finding of the study is a consistent geopolitical gap between production and citation impact. China leads production with 29.8% of the corpus in full counting but records a mean TC of 51.8 citations/doc, while Ireland (333.0), the Netherlands (231.2), and Portugal (221.1)- countries with absolute outputs 5-15 times smaller- generate works that are 4 to 6 times more cited. This pattern is not an anomaly of the MP/NP in food field: it is consistent with the global dynamics of Asian scientific production in emerging fields, where volume grows first and citation quality gradually converges toward international standards in cycles of 8-12 years (Yu *et al.*, 2022).

Three mechanisms explain the gap in this specific field. First, the citation window effect: Chinese works concentrate in 2022-2025 and have between 1 and 4 years to accumulate citations, compared to the pioneering European works of 2015-2018 with 8-11 years. Second, local matrix specificity: Chinese groups preferentially investigate matrices of high domestic consumption- intensive aquaculture shellfish, lake salt, rice, tap water from Chinese cities- which generate lower international citation demand than studies on globally consumed matrices. Third, collaboration network endogamy: China's MCP ratio of 22.1% is the lowest in the top 15, reflecting that the majority of its publications are national works with limited exposure to international citation networks. The most efficient strategy for Chinese groups seeking to increase citation impact is integration into European and

Table 10: Description of the 6 thematic clusters identified by VOSviewer in the keyword co-occurrence network (*n*=708 documents).

Cluster / VOSviewer color	Most representative keywords (TLS)	N kw.	Mean year	Mean cit./doc
C1 - Red Food Safety and Risk Assessment	food safety, risk assessment, human exposure, dietary intake, contamination, occurrence	142	2023.1	72.3
C2 - Green Terrestrial Ecotox. and Agroecosystems	soil, agroecosystem, phytotoxicity, plant uptake, bioremediation, earthworm	118	2023.6	58.1
C3 - Blue Experimental Toxicology and Nanoplastics	nanoplastics, oxidative stress, inflammation, gut microbiota, *in vitro*, zebrafish	127	2023.3	81.4
C4 - Yellow Marine Pollution and Bioaccumulation	marine pollution, seafood, bivalve, fish, ecotoxicology, trophic transfer	155	2022.4	98.6
C5 - Purple Freshwater and Drinking Water Chain	freshwater, drinking water, bottled water, bioaccumulation, river, tap water	136	2022.8	89.2
C6 - Orange Vulnerable Groups and Differential Exposure	children, infant, pregnancy, aged, adolescent, intestine absorption, breast milk	126	2023.5	61.7

Note. TLS: Total Link Strength (sum of link strengths of each keyword with the rest of the network). Mean year: weighted mean publication year of cluster keywords (temporal emergence indicator in VOSviewer overlay). Mean cit./doc: mean citations of documents assigned to the cluster. Network TLS: 284,155. Modularity Q=0.412 (significant threshold Q>0.30). Source: VOSviewer v1.6.x on Scopus corpus *n*=708.

Table 11: Keyword classification by temporal category based on VOSviewer overlay analysis.

Temporal category	Representative keywords	Mean year	Frequency
Consolidated (<2022.5) Dark blue in overlay	seafood, fish, bivalve, marine pollution, ecotoxicology, polystyrene, polyethylene, seawater, particle size, accumulation	<2022.5	High (>40 docs)
Transitional (2022.5-2023.2) Yellow-green in overlay	microplastics, food safety, risk assessment, human health, contamination, drinking water, food packaging	2022.5-2023.2	Very high (>60)
Emerging (>2023.5) Red-orange in overlay	soil pollution, agroecosystem, phytotoxicity, bioremediation, aged microplastics, intestine absorption, infant, adolescent, pregnancy	>2023.5	Low (<20 docs)

Note. Weighted mean year for each keyword is the arithmetic mean of publication years of documents containing that keyword, weighted by co-occurrence frequency. Emergence threshold (mean year >2023.5) equals the corpus median year plus 0.4 years, following Eck and Waltman (2014). Source: VOSviewer v1.6.x, Overlay Visualization on Scopus corpus n=708.

North American collaboration networks, particularly through the East Asia-Europe clusters identified in the VOSviewer map.

This production-impact pattern is consistent with findings reported in prior studies, but the present analysis characterizes it with greater quantitative precision. Yu *et al*. (2022) and Mishra *et al*. (2024)reported the preponderance of China and Western Europe in marine MP, but did not quantify the citation gap. Wong *et al*. (2020) noted that the high productivity of England, China, and the USA is attributable to national funding, but did not analyze the differential impact ratio or identify the underlying mechanisms. The present study contributes three novel analytical elements: (i) precise quantification of the gap- China 51.8 vs. Ireland 333.0 citations/doc, ratio 1:6.4; (ii) explanation of the three causal mechanisms (citation window effect, local matrix specificity, network endogamy with MCP=22.1% for China); and (iii) identification of Spain as an articulating node between Europe and Latin America, which does not appear in any prior antecedent.

Latin America's situation is qualitatively different and warrants specific analysis. Brazil is the only country in the region in the top-15 production ranking (2.3%), with international network insertion mediated primarily through the Spain node. This structural marginality contrasts sharply with the region's high epidemiological relevance: Peru is the world's second-largest fishmeal exporter and has one of the highest dietary MP exposures via seafood globally; most Latin American countries exhibit limited food contact material regulation; and the prevalence of low-cost plastic bottled water consumption- with scarce quality control over MP migration- is high throughout the region. The Latin American research agenda on MP in food is underdeveloped relative to its actual relevance for regional public health, and represents a research opportunity with high potential international citation demand. The most efficient insertion strategy for Latin American groups is to build collaborations with the Spain node (C1 in the VOSviewer map), which acts as a bridge toward the highest-impact European networks.

The cognitive architecture of the field and priority research frontiers

The keyword co-occurrence map of the present study (6 clusters, Q=0.412, TLS=284,155) offers greater thematic resolution than the five most directly comparable antecedents reviewed in Section 1.2. He *et al*. (2020) used VOSviewer for terrestrial ecosystems but did not report modularity Q or differentiate more than three or four themes. Jin *et al*. (2022) applied CiteSpace and COOC for detection techniques, identifying two main networks, but without constructing a thematic map of the field as a whole. Mishra *et al*. (2024) - the most comparable study in scale- used biblioshiny to identify 22 trending topics in marine MP, but without resolving clusters with the Louvain algorithm or reporting network metrics (TLS, Q). Jamil *et al*. (2025) applied social network analysis to MP in agroecosystems with an exclusively agricultural focus, without direct traceability to consumed food. The resolution of 6 clusters (Q=0.412, 266 nodes, TLS=284,155) exceeds the cluster differentiation reported by the five comparable antecedents reviewed in Section 1.2, none of which reported modularity Q or more than four thematic clusters for this subdomain.

The VOSviewer keyword co-occurrence map reveals a dual cognitive architecture- environmental-ecological axis versus biomedical-toxicological axis- reflecting the interdisciplinary nature of the field and, simultaneously, an unresolved structural tension: environmental ecotoxicology and medical toxicology researchers work on the same object (MP/NP in food for human consumption) from different paradigms, methodologies, and journals, with limited real integration. The absence of a cluster dedicated to the nutritional epidemiology of MP- which would explicitly connect MP concentrations in food with health effects in cohort or case-control studies- is the clearest bibliometric signal of this interdisciplinary gap. Building that bridge represents one of the field's most pressing methodological challenges for the coming years.

The three emerging frontiers identified by temporal overlay are consistent with trends signaled by recent antecedents but are characterized with greater quantitative rigor. He *et al*.

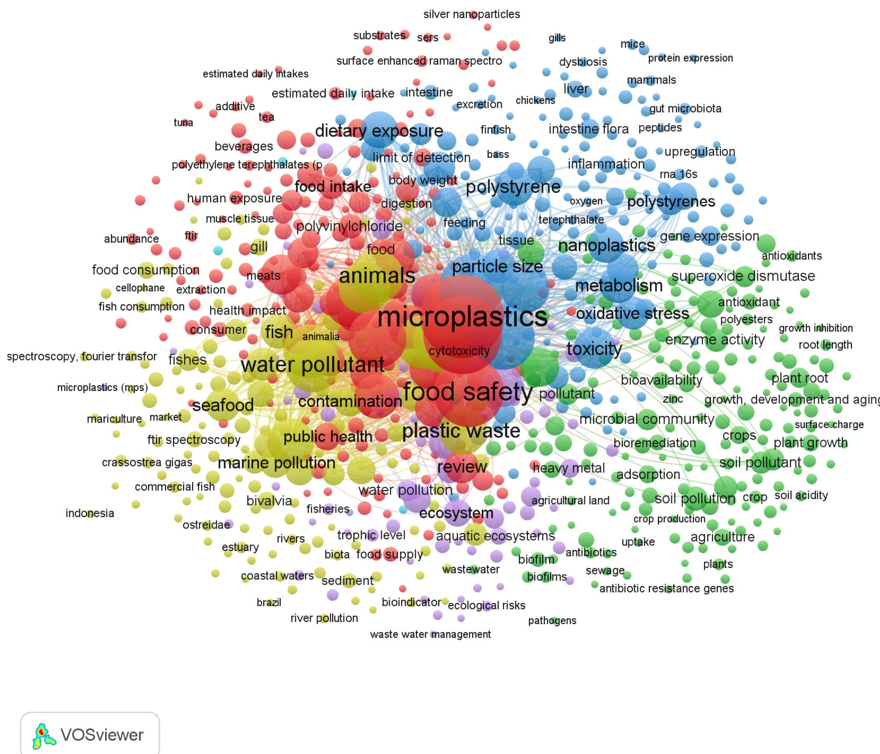

Figure 2: VOSviewer keyword co-occurrence map (266 nodes, 92,490 links, 6 clusters, modularity Q=0.412). Node size proportional to frequency; color by cluster; node distance proportional to co-occurrence strength.

(2020) and Yu *et al.* (2022) anticipated the expansion toward terrestrial ecosystems, but lacked post-2022 data to document its acceleration. Li *et al.* (2022) reviewed scientometric trends in microplastics research, and Ruan *et al.* (2024) explored phytoremediation at land-sea interfaces; both studies validate the emergence of cluster C2 in the present analysis (terrestrial ecotox., mean year 2023.6). Ebrahimi *et al.* (2022) highlighted human health risks from ingestion and inhalation, anticipating cluster C6 (vulnerable groups, mean year 2023.5), but no prior antecedent had temporally quantified the co-emergence of keywords such as infant, pregnancy, adolescent, and intestinal absorption that the present study's overlay detects with annual resolution.

Temporal overlay analysis suggests three candidate emerging research frontiers as of March 2026, based on the weighted mean publication year criterion (>2023.5). The first is the ecotoxicology of terrestrial agroecosystems (cluster C2, mean year 2023.6): The keywords phytotoxicity, plant uptake, agroecosystem, and bioremediation signal a shift in research focus from aquatic toward terrestrial ecosystems, with direct implications for the safety of short-cycle horticultural crops (lettuces, spinach, strawberries) that absorb MP from soil through their roots. This front has particular relevance for countries with intensive plastic-covered agriculture and high dependence on sewage sludge as fertilizer.

The second frontier is the biotechnology of MP bioremediation in soils and water (also in C2): keywords bioremediation and degradation point to a nascent field seeking biotechnological solutions for the removal of MP from environmental matrices that form part of the food chain. This front connects MP research with environmental biotechnology and biodegradable plastic design, generating a genuinely new thematic space with high funding potential within circular economy policy frameworks.

The third and most urgent frontier is differential toxicology in vulnerable groups (cluster C6, mean year 2023.5). The simultaneous emergence of keywords such as children, infant, pregnancy, aged, and adolescent alongside intestinal absorption and gut microbiota signals that the field is undergoing a critical epistemological transition: moving from detection and quantification studies of MP/NP in food matrices toward mechanistic and differential toxicokinetic studies- what fraction of ingested MP/NP crosses the intestinal barrier in each age group? Key open questions include the effect of the developing infant gut microbiota on NP absorption, and whether prenatal NP exposure affects fetal neurodevelopment. These questions require the massive incorporation of molecular biology, metabolomics,

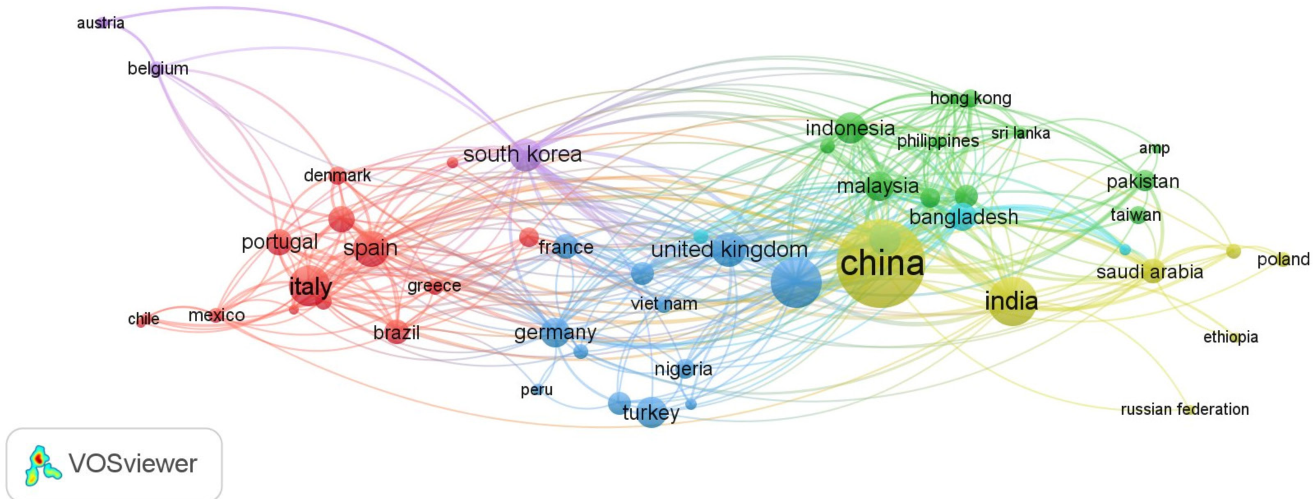

Figure 3: VOSviewer temporal overlay map: color gradient from blue (older publications) to red (recent publications). Corpus median year: 2023.1; keywords with weighted mean year >2023.5 are classified as emerging.

and physiologically based pharmacokinetic (PBPK) toxicokinetic models that are currently underrepresented in the corpus, suggesting that the field is at the beginning of a large-scale methodological transition.

Finally, the fact that Foods (MDPI) is the only food science journal in the Bradford core- with 22 documents compared to 47 for Environmental Pollution- suggests that the field has not yet found its definitive editorial home in the food sciences. This is, paradoxically, good news for journals specializing in food safety: they have a clear window of opportunity to consolidate their position as preferred publication platforms as the field matures toward dietary risk assessment.

CONCLUSION

The bibliometric and scientometric analysis of the Scopus corpus (*n*=708; 2015-2025) yields the following conclusions:

The field has reached substantial bibliometric maturity within eleven years (CAGR=55.25%; H=102), with 77.1% of production concentrated in 2023-2025, generating a structurally growing regulatory lag- the empirical base has grown nearly fivefold since EFSA 2020. (EFSA Panel on Contaminants in the Food Chain, 2016) Regulatory bodies (EFSA, WHO, Codex Alimentarius) should establish formal biennial evidence update cycles.

The Bradford distribution (8:53:205; ratio ≈ 1: n: n^2, $n \approx 7$) confirms corpus bibliometric validity. All 8 core journals are Q1; 6 belong to the environmental sciences. Foods (MDPI) is the sole food science representative, signaling a strategic opportunity for journals such as Food Control or Food Quality and Safety.

A systematic geopolitical production-impact gap exists: China leads in volume (29.8%, mean TC=51.8) while Ireland (333.0), the Netherlands (231.2), and Portugal (221.1) lead in impact with 5-15 times smaller outputs. Spain articulates the Mediterranean bloc with Latin America. Brazil is the region's sole top-15 representative, despite Latin America's high epidemiological relevance.

The VOSviewer map (266 nodes, TLS=284,155, Q=0.412) reveals a dual cognitive architecture- environmental-ecological versus biomedical-toxicological- with limited interdisciplinary integration. The 6 clusters range from consolidated marine pollution (C4, mean year 2022.4) to emerging terrestrial ecotoxicology (C2, 2023.6) and vulnerable groups (C6, 2023.5). The absence of a nutritional epidemiology cluster represents a salient interdisciplinary gap in the field's cognitive architecture.

Temporal overlay identifies three priority research fronts for 2026-2030

(a) agroecosystem ecotoxicology and phytotoxicity in edible crops; (b) MP bioremediation biotechnology in soils and water; and (c) differential toxicology in vulnerable groups- infants, pregnant women, older adults- focusing on intestinal NP absorption and microbiota effects, the front of greatest regulatory urgency.

Latin American research groups are recommended to: (i) prioritize dietary exposure studies in high-consumption regional matrices (seafood, bottled water, plastic-wrapped foods); (ii) build collaborations through the Spain node for insertion into high-impact international networks; and (iii) target the 8 Bradford core journals to maximize citation visibility.

Study limitations

(i) exclusive use of Scopus, with possible exclusion of documents indexed solely in Web of Science, PubMed, or regional databases; (ii) full-counting affiliation may overestimate small-country contributions in multi-author works; (iii) 2025 documents have a ≤12-month citation window, insufficient for robust co-occurrence calculations; and (iv) no author co-citation analysis or bibliographic coupling were performed. Future studies should combine keyword co-occurrence with co-citation analysis for a more complete picture of the field's intellectual structure. (v) The exclusion of non-English documents from any bibliometric analysis of the scientific literature can introduce a linguistic bias that may result in an incomplete estimate of the total amount of scientific output from non-English research communities. A substantial proportion (13.5%) of peer-reviewed Chinese, Spanish, Portuguese, and Arabic-language journals indexed in Scopus is thus excluded from consideration based on the applied filter. Furthermore, the evidence suggests that English-limited datasets in the environmental sciences can result in the underreporting of non-English output by 8-15%, disproportionately impacting the data from emerging economies (Mongeon and Paul-Hus, 2016). For MP/NP research specifically, this bias is particularly consequential for Chinese and Latin American production, as both regions host active research communities that publish partly in local languages. Future bibliometric studies should consider multi-language corpus construction or, at minimum, quantify the volume of excluded non-English documents to bound this source of bias.

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ABBREVIATIONS

MP: Microplastics; **NP:** Nanoplastics; **CAGR:** Compound Annual Growth Rate; **TC:** Total Citations; **TLS:** Total Link Strength; **MCP:** Multiple Country Publications; **PRISMA:** Preferred Reporting Items for Systematic Reviews and Meta-Analyses; **VOSviewer:** Visualization of Similarities viewer; **SJR:** SCImago Journal Rank; **EFSA:** European Food Safety Authority; **WHO:** World Health Organization; **PBPK:** Physiologically Based Pharmacokinetic; **CRediT:** Contributor Roles Taxonomy; **FTIR-ATR:** Fourier-Transform Infrared Spectroscopy-Attenuated Total Reflectance; **GC/MS:** Gas Chromatography/Mass Spectrometry; **CRAN:** Comprehensive R Archive Network.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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DATA AVAILABILITY

The complete bibliographic corpus (n=708 records, bib format), R analysis scripts (bibliometrix v4.x), and VOSviewer network files (.vos,.txt) are available upon reasonable request to the corresponding author.

AUTHOR CONTRIBUTIONS

J.E.P.Z.: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing - original draft, Writing - review & editing. J.M.B.: Writing - review & editing, Validation. J.H.C.: Writing - review & editing, Validation. M.H.M.: Writing - review & editing, Validation.

DECLARATION OF AI USE

The authors used Claude (Anthropic) as an AI-assisted writing tool to improve the clarity, fluency, and English translation of this manuscript. The AI tool was used exclusively for language editing and translation purposes. All scientific content, data analysis, interpretation of results, and conclusions are entirely the authors' own. The authors take full responsibility for the accuracy and integrity of the work.

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Appendix A. Full Boolean search string executed in Scopus

The following string was executed verbatim in Scopus (Elsevier) on March 9, 2026, at 14:32 h (UTC−5), using institutional access provided by Universidad de San Martín de Porres (USMP), Filial Sur:

TITLE-ABS-KEY (("microplastic*" OR "nanoplastic*" OR "plastic particle*" OR "plastic debris") AND ("food" OR "beverage*" OR "seafood" OR "fish" OR "shellfish" OR "water" OR "salt" OR "honey" OR "milk" OR "vegetable*" OR "fruit*" OR "meat" OR "packaging" OR "bottled") AND ("human" OR "dietary" OR "exposure" OR "contamination" OR "ingestion" OR "safety" OR "health")) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND DOCTYPE (ar OR re) AND LANGUAGE (english)

Records retrieved before PRISMA screening: n=980. Search fields: TITLE-ABS-KEY. Document types: Article (ar) and Review (re). Language: English. Period: 2015-2025.