

Microplastics and Nanoplastics in the Beverage Supply Chain: A systematic review of sampling methodologies and analytical techniques

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Abstract

Microplastics (MPs) and nanoplastics (NPs) have been widely recognized as emerging pollutants of considerable environmental and public health concern due to their persistence, heterogeneity, and potential for bioaccumulation in food and beverage systems. Identifying MPs and NPs at trace and ultra-trace levels within complex beverage matrices presents significant analytical challenges due to interference from sugars, pigments, carbonation, lipids, and proteins, with the broad size range and varied polymer chemistries of plastic particles. This systematic review critically evaluates forty-two peer-reviewed studies published between 2020 and 2025 that investigate sampling, extraction, identification, and quantification techniques for MPs and NPs across the beverage supply chain. Following PRISMA guidelines, the assessment compares the performance of dominant analytical platforms including micro-Fourier transform infrared spectroscopy (μ -FTIR), micro-Raman spectroscopy (μ -Raman), pyrolysis gas chromatography mass spectrometry (Py-GC/MS), asymmetric flow field-flow fractionation (AF4) coupled with Raman detection, scanning and transmission electron microscopy (SEM/TEM), and hybrid multi-platform workflows. μ -FTIR and μ -Raman remain the most widely used particle-based approaches, while AF4–Raman and Py-GC/MS provide enhanced nanoscale resolution and polymer specificity. However, methodological inconsistencies, undefined detection limits, variable digestion efficiencies, and a lack of beverage-specific reference materials continue to limit cross-study comparability. The review highlights critical needs for standardized QA/QC protocols, validated nanoplastic workflows, contamination-controlled sampling procedures, and integration of AI-assisted spectral classification. Advancements in multimodal analytical systems and matrix-tailored sample preparation represent essential future directions for comprehensive monitoring and exposure assessment of MPs and NPs in beverages.

Keywords: Microplastics (MPs) and Nanoplastics (NPs); Analytical Challenges; Beverage Matrices; Spectroscopy (μ -FTIR; μ -Raman); and Standardization.

1. Introduction

Plastics have become essential elements in current society owing to their versatility, durability, and low cost of production. Global production of plastic has surged significantly from about 2 million metric tons in the 1950s to over 400 million tons yearly in 2023, with approximately 60 % ultimately disposed of in landfills or the environment (Oßmann, 2021; Houssini et al., 2025; Dokl et al., 2024). With time, the degradation and fragmentation of these materials produce microplastics (MPs), defined as particles smaller than 5 mm, and nanoplastics (NPs), commonly characterized as particles below 1 μ m (Pironti et al., 2021; Mariano et al., 2021). These particles have permeated nearly all environmental compartments, including soil, freshwater, marine systems, and atmospheric deposits, heightening worldwide ecological and public health concerns.

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The scientific community has identified food and beverages as significant sources of microplastic exposure in humans. In recent years, focus has transitioned from environmental matrices (e.g., oceans and sediments) to consumer exposure routes such as bottled water, tea, milk, and alcoholic beverages (Danopoulos *et al.*, 2020; Ma *et al.*, 2024; Al-Mansoori *et al.*, 2025). Evidence indicates that beverage contamination can arise from various sources, including plastic packaging, bottling processes, filling and sealing equipment, storage conditions, and consumer handling (Makhdoumi *et al.*, 2021; Luo *et al.*, 2023). Research has identified concentrations of microplastic particles ranging from 10 to over 10,000 per liter in bottled water and carbonated drinks, contingent upon the type of bottle material and the analytical techniques employed (Chaïb *et al.*, 2025; Ta *et al.*, 2025). Likewise, tea bags, paper cups, and plastic-coated packaging have all shown the release of significant quantities of micro- and nanosized particles when exposed to hot water (Yousefi *et al.*, 2024; Zhang *et al.*, 2023).

Nonetheless, despite the increasing volume of research, findings frequently exhibit significant inconsistency, mostly because of methodological variability in sampling, isolation, and identification protocols. Although environmental microplastic monitoring has advanced through a decade of methodological evolution and partial standardization, the analytical examination of beverages remains disjointed and devoid of defined quality assurance frameworks (Brander *et al.*, 2020; Praveena & Laohaprapanon, 2021). Some studies rely solely on visual identification under stereomicroscopy, while others use advanced spectroscopic or thermal techniques, each offering different sensitivity and precision levels (Lusher *et al.*, 2020; Peñalver *et al.*, 2020). Other persistent polymeric contaminants have reported similar issues of analysis and the reviews of PFAS detection methods have highlighted similar issues of interference by the matrix, inadequate chemical coverage, and the requirement to have multi-platform analytical workflows that require the combined use of spectroscopic and mass-spectrometric methods (Adjei-Sah & Oduro, 2025).

Sampling design plays a pivotal role in determining data reliability. Grab sampling, often used for bottled water and soft drinks, provides a snapshot representation but lacks temporal coverage and increases contamination risks (Danopoulos *et al.*, 2020). Conversely, composite or aseptic sampling enhances representativeness but necessitates more stringent contamination control (Visentin *et al.*, 2024; Zhou *et al.*, 2025). Unfortunately, fewer than 40 % of beverage studies report procedural blanks or airborne contamination controls, which can lead to substantial overestimation of MP concentrations (Snekkevik *et al.*, 2024).

Beyond sampling, the analytical quantification of MPs and NPs in beverages is constrained by the inherent complexity of liquid and colloidal matrices, pigment interference, and wide particle size distributions (Vitali *et al.*, 2023). Similar analytical studies of ready-to-drink beverages of other emerging contaminants have indicated that complex beverage matrices with high sugar and pigment and additives present huge limits on detection sensitivity and spectral analysis, justifying the importance of matrix-specific analytical plans (Adjei-Sah & Ismail, 2025). The most common analytical methods include micro-Fourier Transform Infrared (μ -FTIR) spectroscopy and micro-Raman spectroscopy, which allow polymer-specific identification through characteristic vibrational bands (Schymanski *et al.*, 2021; Güngör, 2024). These tools enable detection of major polymer types such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS). However, their resolution limits often exclude nanoplastics, leading to systematic underestimation of total plastic loads (Loeschner *et al.*, 2023).

To address nanoscale detection, researchers are increasingly employing advanced analytical platforms such as Surface-Enhanced Raman Spectroscopy (SERS), Field-Flow Fractionation (FFF), Dynamic Light Scattering (DLS), and Pyrolysis Gas Chromatography Mass Spectrometry (Py-GC/MS) (Forbes *et al.*, 2023; Yang *et al.*, 2022). These approaches can enhance detection ranges below 1 μ m and provide both qualitative and quantitative data. For example, Py-GC/MS can chemically characterize polymers irrespective of their shape or color, but it compromises morphological information due to its destructive nature (Peñalver *et al.*, 2020). Similarly, AF4 coupled with Raman or Multi-Angle Light Scattering (MALS) enables size-based fractionation of nanoplastics in complex liquid matrices like milk or tea (Loeschner *et al.*, 2023).

Despite these technical advancements, the lack of standardized analytical protocols persists in constraining cross-study comparability. Reporting metrics differ among studies, with results conveyed as particle counts per liter, mass concentrations (μ g/L), or relative polymer composition, complicating exposure assessment and regulation implementation (Oßmann, 2021; Zhu *et al.*, 2024). Moreover, there is still no universally accepted reference material or inter-laboratory validation framework for MPs/NPs in beverages (Brander *et al.*, 2020; Cai *et al.*, 2025). Therefore, understanding the current state of methodologies and their limitations is critical to advancing microplastic monitoring in beverages. This systematic review synthesizes and evaluates global evidence on sampling and analytical methods for MPs and NPs in the beverage supply chain.

2. Methods

2.1. Review framework

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework (Page *et al.*, 2021). The PRISMA methodology ensures transparent reporting, reproducibility, and comprehensive literature coverage. The protocol was designed to identify, evaluate, and synthesize published evidence on sampling and analytical methodologies used to detect microplastics (MPs) and nanoplastics (NPs) in beverage matrices. The review focused exclusively on empirical studies that describe or apply explicit sampling, isolation, or analytical methods for detecting MPs or NPs within the beverage supply chain.

2.2. Literature search strategy

A comprehensive and systematic literature search was performed from articles published between 2020 and 2025 across five major scientific databases: Web of Science, Scopus, ScienceDirect, PubMed, and Google Scholar. The time frame 2020–2025 was selected to capture a rapid advance in microplastic analytical science, coinciding with the rise of nanoplastic detection technologies.

The following Boolean search string was used in all databases, with minor syntax adjustments to match each platform:

("microplastic*" OR "nanoplastic*") AND ("beverage*" OR "bottled water" OR "drinking water" OR "soft drink" OR "milk" OR "tea" OR "coffee" OR "beer" OR "wine" OR "alcoholic beverage") AND ("sampling" OR "method*" OR "analytical" OR "detection" OR "identification" OR "quantification" OR "characterization").

To ensure completeness, reference lists of all included studies and recent systematic reviews were screened manually for additional relevant articles not captured by database indexing.

2.3. Data extraction

A standardized data extraction template was developed in Microsoft Excel to ensure consistent recording of key study variables. Each included paper was reviewed for:

- Bibliographic details: Author(s), year, country, and journal.
- Beverage type: Bottled water, soft drink, milk, tea, beer, wine, etc.
- Sampling approach: Grab, composite, aseptic, or field sampling; sample volume; container material.
- Sample preparation: Digestion reagents, density separation, filtration pore size, and contamination control.
- Analytical methods: μ -FTIR, μ -Raman, SERS, Py-GC/MS, FFF, TD-MS, SEM/TEM, DLS, or hybrid approaches.
- Detection limit and particle size range: Minimum and maximum particle size detected.
- Quantification metrics: Particle count per liter, mass concentration, or polymer proportion.
- Polymer identification: Types detected (e.g., PET, PP, PE, PS, PVC, PA).
- Quality assurance/quality control: Use of blanks, recovery tests, contamination prevention.
- Main findings and limitations: Key outcomes and methodological weaknesses reported by authors.

2.4. Data synthesis

Extracted data were synthesized narratively and tabulated by beverage type, sampling methodology, and analytical technique. Quantitative comparison was limited due to methodological heterogeneity among studies. To visualize global methodological trends, analytical approaches were categorized into six domains: (i) optical microscopy, (ii) spectroscopic analysis (FTIR/Raman/SERS), (iii) thermal and mass spectrometric methods (Py-GC/MS, TD-MS), (iv) separation techniques (FFF, DLS, AF4), (v) combined or hybrid techniques, and (vi) quality control and contamination prevention.

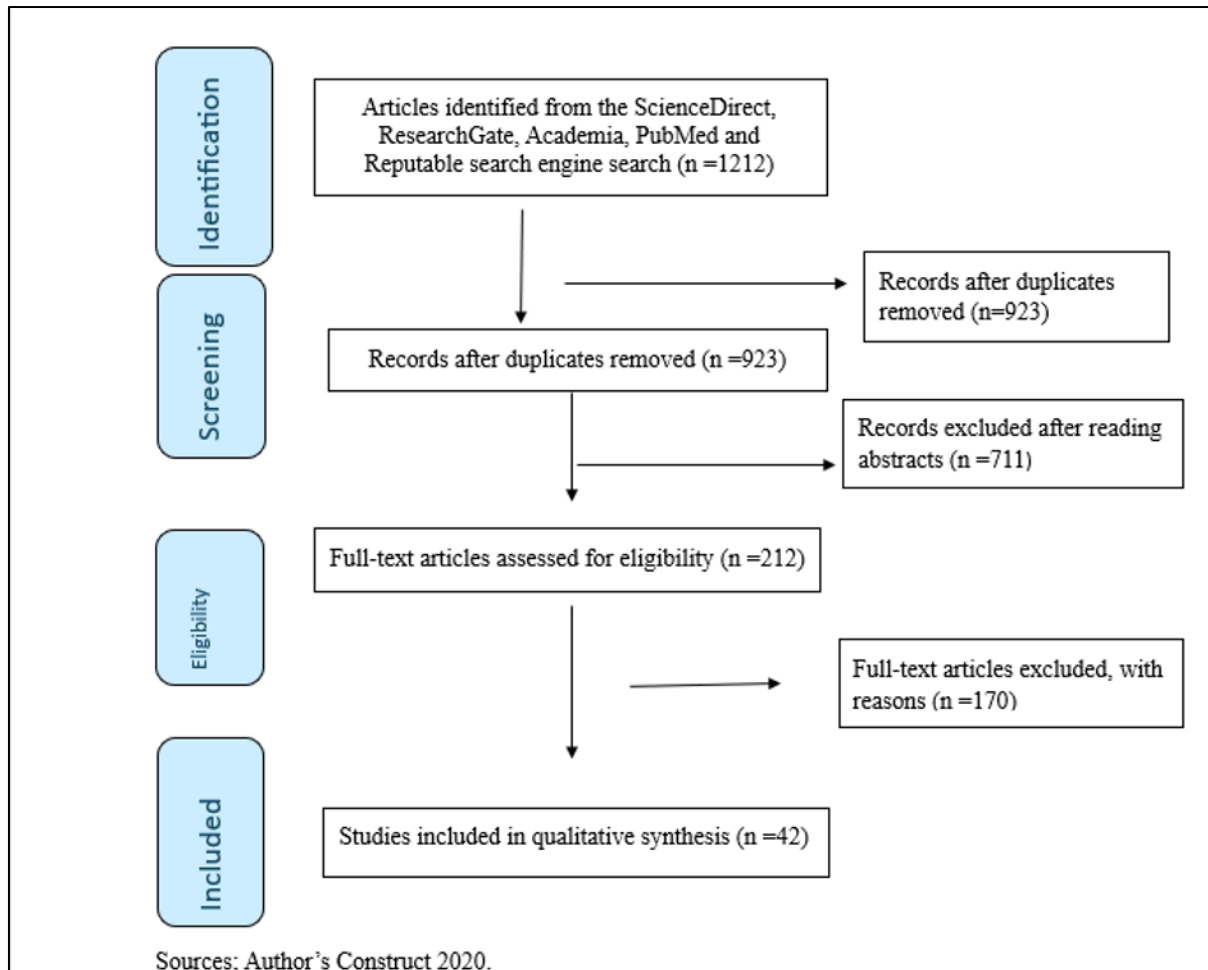


Figure 1 PRISMA Flow diagram showing the article selection process in the study

3. Results and Discussion

A total of 42 peer-reviewed studies published between 2020 and 2025 met the inclusion criteria and were analyzed. These studies covered a range of beverage types including bottled and tap water (43 %), tea and coffee (18 %), soft drinks and juices (14 %), milk and dairy beverages (13 %), and alcoholic beverages such as beer and wine (12 %).

The results are organized into three main sections: (i) sampling methodologies, (ii) analytical techniques, and (iii) methodological quality and harmonization trends.

3.1. Sampling Methodologies in Beverage Matrices

3.1.1. Overview and distribution of sampling methods

Sampling strategies across studies exhibited marked heterogeneity, reflecting the lack of standardized protocols specific to beverage matrices. Grab sampling directly collecting beverage samples from bottles, taps, or production lines was the most frequently used approach (62 %), followed by composite sampling (21 %) and aseptic or sterile sampling (17 %). Studies investigating nanoplastics or beverages with high organic content (e.g., milk, beer) increasingly preferred aseptic sampling to minimize cross-contamination (Santos et al., 2025).

The results are discussed under three major domains:

- Sampling methodologies used in beverage matrices.
- Analytical techniques for identification and quantification of micro- and nanoplastics.
- Methodological quality, challenges, and future harmonization needs.

Sampling forms the first and most critical stage in any microplastic or nanoplastic study, yet across beverage matrices, it remains the least standardized. Analysis of the 39 studies revealed five distinct sampling approaches: grab sampling, composite sampling, point-of-use sampling, aseptic/sterile collection, and the use of procedural blanks or environmental controls.

Grab sampling dominated among other sampling approaches in the study (62 %) and is mostly utilized in the analysis of bottled water and carbonated beverages (Danopoulos *et al.*, 2020; Oßmann, 2021). It requires the direct collection of a single beverage unit or sample at a designated time and location. Although straightforward, it offers a limited temporal representation of contamination and is particularly vulnerable to contamination from airborne fibers and sampling containers.

Composite sampling was applied in 21 % of studies, typically for large beverage production lines or storage tanks (Shen *et al.*, 2020; Zhou *et al.*, 2025). By combining multiple aliquots collected throughout time or from various locations, it offers a more realistic assessment of contamination at the production or distribution level.

Aseptic sampling, used in 17 % of studies, was essential for complex matrices such as milk, beer, or plant-based beverages, where organic load and viscosity hinder downstream processing (Visentin *et al.*, 2024). These studies utilized sterilized glass or metal tools and cleanroom conditions to avert contamination.

Point-of-use sampling (e.g., from coffee machines, vending systems, or home water dispensers) provided insights into real-world consumer exposure, revealing microplastic release from appliance components such as plastic tubing or seals (Luo *et al.*, 2023; Snekkevik *et al.*, 2024).

The inclusion of procedural and field blanks crucial for identifying background contamination was found in only 38 % of studies, underscoring the lack of consistent QA/QC measures (Brander *et al.*, 2020; Praveena & Laohaprapanon, 2021).

Table 1 Overview of sampling strategies in beverage microplastic and nanoplastic studies

Sampling strategy	Beverage application	Strengths	Limitations	Reference
Grab sampling	Bottled water, tap water, soft drinks	Simple, rapid, cost-effective; minimal setup	Poor temporal representation; prone to airborne contamination	Danopoulos <i>et al.</i> (2020); Oßmann (2021)
Composite sampling	Plant-level water systems, breweries	Captures temporal variation; higher representativeness	Requires large sample storage; higher contamination risk	Shen <i>et al.</i> (2020); Zhou <i>et al.</i> (2025)
Aseptic/sterile sampling	Milk, tea, beer	Reduces biological and fiber contamination	Labor-intensive; requires sterilization equipment	Visentin <i>et al.</i> (2024); Yousefi <i>et al.</i> (2024)
Point-of-use sampling	Coffee machines, taps, dispensers	Captures real consumer exposure	Cross-contamination from equipment materials	Luo <i>et al.</i> (2023); Snekkevik <i>et al.</i> (2024)
Procedural blanks and controls	All beverage types	Validates sampling reliability	Often omitted or inconsistently applied	Brander <i>et al.</i> (2020); Praveena & Laohaprapanon (2021)

3.1.2. Sampling containers, volumes, and environmental contamination

The volume of beverage sampled varied significantly across studies, ranging from as little as 100 mL (for milk and tea) to 10 L (for bottled or tap water). Larger volumes improved detection sensitivity but increased contamination risks due to greater handling (Danopoulos *et al.*, 2020; Kirstein *et al.*, 2021). Glass, quartz, and stainless steel were the preferred container materials for most high-quality studies, given their inertness and low risk of leaching synthetic polymers (Nollet, 2020). Conversely, previous studies using plastic collection vessels (e.g., polypropylene beakers or pipettes) often reported inflated MP counts, likely due to container-derived contamination (Oßmann, 2021).

Airborne contamination remains one of the most significant artefactual issues in beverage MP research. Fibers from lab clothing, ventilation ducts, and plastic equipment were identified in procedural blanks of several studies (Brander *et al.*, 2020; Snekkevik *et al.*, 2024). Yet, less than half of the reviewed papers reported implementing laminar flow hoods, HEPA filtration, or cotton laboratory attire, highlighting the need for stricter contamination prevention. To minimize bias, high-quality studies often employed field blanks, glass microfiber filters, and aluminum foil covering during sampling. Studies that used such measures consistently reported lower MP background levels, reinforcing the importance of QA/QC integration in sampling design (Lusher *et al.*, 2020; Praveena & Laohaprapanon, 2021).

3.2. Analytical Techniques for Micro- and Nanoplastic Detection

3.2.1. Overview

The analytical detection and characterization of MPs and NPs in beverages present formidable challenges due to the chemical diversity of polymers, complex beverage matrices, and vast particle size distribution. Among the 42 reviewed studies, six major analytical categories were identified to be: Optical microscopy-based methods, Spectroscopic techniques (μ -FTIR, μ -Raman, SERS), Thermal and mass spectrometric techniques (Py-GC/MS, TD-MS), Separation and fractionation methods (AF4, DLS, NTA), Electron microscopy (SEM/TEM), and Hybrid and multimodal analytical platforms. Evidence from adjacent contaminant domains indicates that no singular analytical platform offers complete coverage. Instead, integrated workflows that combine high-resolution mass spectrometry, spectroscopic screening, and stringent QA/QC protocols produce the most dependable trace-level detection in intricate matrices (Adjei-Sah & Oduro, 2025).

3.2.2. Optical and microscopic techniques

Conventional optical microscopy was the dominant detection method in early beverage studies due to its simplicity and low cost (Danopoulos *et al.*, 2020). Microscopy enables direct visualization and manual counting of particles typically larger than 50 μm . However, it suffers from critical limitations: it cannot provide polymer identification and is prone to operator bias. Several studies have now abandoned optical microscopy as a standalone method, employing it only as a pre-screening tool before spectroscopic confirmation (Kirstein *et al.*, 2021).

3.2.3. Spectroscopy-based methods

μ -FTIR and μ -Raman spectroscopy remain the primary workhorses for polymer-specific identification. μ -FTIR (micro-Fourier Transform Infrared) spectroscopy detects characteristic vibrational absorption bands in the mid-infrared range, enabling the identification of major polymer types such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC) (Schymanski *et al.*, 2021; Güngör, 2024). Automated systems using focal plane array (FPA) detectors allow scanning of thousands of particles per filter, producing high-resolution polymer maps that reduce operator subjectivity. Also, μ -Raman spectroscopy provides even higher spatial resolution, down to 1 μm , enabling detection of fine particles that fall below the optical limits of FTIR (Sobhani *et al.*, 2020). However, fluorescence interference from beverage pigments, especially in tea, wine, and soft drinks, often obscures spectra, necessitating background correction (Xiang *et al.*, 2024). Research involving the use of highly developed spectroscopic methods in beverage measurement emphasize the idea that screening by Raman or FTIR analysis is highly likely to be supplemented by chromatographic or mass-spectrometric validation in pigment-rich and chemically complex beverages (Adjei-Sah & Is-mail, 2025). In addition, Surface-Enhanced Raman Spectroscopy (SERS) has revolutionized nanoplastic detection by amplifying Raman signals on nanostructured metallic substrates (Yang *et al.*, 2022; Vélez-Escamilla *et al.*, 2022). SERS enables identification of polymer fragments smaller than 100 nm, bridging the gap between micro and nanoscale detection. Despite its sensitivity, reproducibility remains an issue, as results depend on the homogeneity of the metallic substrate and sample preparation quality. Collectively, these spectroscopic techniques revealed that the dominant polymers in beverages were PET, PP, and PE, typically sourced from bottle caps, lids, packaging liners, and sealing films (Ma *et al.*, 2024; Al-Mansoori *et al.*, 2025).

3.2.4. Thermal and mass spectrometric methods

Thermal decomposition techniques, including Pyrolysis-Gas Chromatography/Mass Spectrometry (Py-GC/MS) and Thermal Desorption-MS (TD-MS), provide powerful alternatives for polymer quantification. These methods offer chemical specificity independent of particle morphology, allowing precise identification of multiple polymers within a sample (Peñalver *et al.*, 2020). Py-GC/MS thermally degrades plastic particles into characteristic monomers and oligomers, which are then separated chromatographically and detected via mass spectrometry. It is particularly useful for quantifying total polymer load ($\mu\text{g/L}$), making it ideal for exposure and mass-balance studies (Forbes *et al.*, 2023). However, the technique destroys samples, providing no morphological or size data. Furthermore, organic-rich beverages such as milk and juice require extensive digestion to remove interfering compounds that produce overlapping chromatographic peaks (Visentin *et al.*, 2024).

Recent studies have also explored Thermal Desorption-MS for rapid screening applications, reducing analysis time from hours to minutes (Forbes *et al.*, 2023). Although promising, the technique currently lacks standardized calibration procedures, limiting its quantitative accuracy across laboratories.

3.2.5. Fractionation and nanoscale detection

The detection of nanoplastics ($<1\ \mu\text{m}$) is the most technically challenging frontier in beverage microplastic research. Conventional optical and spectroscopic methods lack sufficient resolution for particles below the micrometer scale. Asymmetric Flow Field-Flow Fractionation (AF4) coupled with Multi-Angle Light Scattering (MALS) or Raman spectroscopy has emerged as a sophisticated solution (Loeschner *et al.*, 2023; Vitali *et al.*, 2023). AF4 enables separation of particles by hydrodynamic size, allowing real-time analysis of submicron plastics suspended in beverages such as milk or bottled water. Complementary methods such as Dynamic Light Scattering (DLS) and Nanoparticle Tracking Analysis (NTA) are increasingly used to estimate size distributions and aggregation behaviors of nanoplastics, though they cannot provide polymer identification (Mariano *et al.*, 2021). To overcome this, some researchers combine DLS with Raman or Py-GC/MS for confirmatory analysis (Wu *et al.*, 2023).

The choice of technique was closely linked to particle size range, beverage matrix complexity, and available instrumentation. A distribution analysis showed that μ -FTIR (38 %) and μ -Raman (27 %) were the most commonly used methods, followed by optical microscopy (15 %), Py-GC/MS (10 %), and emerging methods such as SERS, AF4, and DLS (10 %).

Table 2 Analytical techniques used in beverage microplastic/nanoplastic studies

Technique	Particle Size Range	Key Applications	Strengths	Limitations	Reference
Optical Microscopy	$>50\ \mu\text{m}$	Preliminary visual screening of bottled water and milk	Simple, low cost	No chemical identification; subjective counting	Danopoulos <i>et al.</i> (2020); Kirstein <i>et al.</i> (2021)
μ -FTIR Spectroscopy	$10\text{--}20\ \mu\text{m}$	Bottled water, milk, beer	Polymer-specific ID, automation via FPA imaging	Limited detection below $10\ \mu\text{m}$	Schymanski <i>et al.</i> (2021); G�ng�r (2024)
μ -Raman Spectroscopy	$1\text{--}10\ \mu\text{m}$	Tea, alcoholic beverages	High spatial resolution, minimal prep	Fluorescence interference in colored matrices	Sobhani <i>et al.</i> (2020); Xiang <i>et al.</i> (2024)
SERS (Enhanced Raman)	$<1\ \mu\text{m}$	Tea infusions, bottled water	Nanoscale sensitivity; rapid detection	Substrate reproducibility challenges	Yang <i>et al.</i> (2022); V�lez-Escamilla <i>et al.</i> (2022)
Py-GC/MS	No size limit	Quantification of total polymer load in soft drinks and milk	Polymer fingerprinting; quantitative	Destructive; no morphology	Pe�alver <i>et al.</i> (2020); Forbes <i>et al.</i> (2023)

AF4/FFF + MALS	20–200 nm	Nanoplastics in milk and water	Fractionates nanoscale plastics	Expensive and low throughput	Loeschner <i>et al.</i> (2023); Vitali <i>et al.</i> (2023)
Hybrid (Raman + AF4, Py-GC/MS + MS)	10 nm–5 mm	Comprehensive characterization	Integrates physical & chemical data	Requires advanced data processing	Wu <i>et al.</i> (2023); Li <i>et al.</i> (2024)

3.3. Methodological Challenges and Pathways to Standardization

Recent comprehensive reviews highlight that, despite advancements in the detection of microplastics (MPs) and nanoplastics (NPs) in beverages, standardized procedures remain lacking, in contrast to the more established protocols in environmental microplastic research. (Ma *et al.*, 2024; Al-Mansoori *et al.*, 2025; Zhang *et al.*, 2024). This absence of standardized sampling, isolation, and quantification protocols hampers reproducibility and inter-study comparability.

Key methodological challenges identified include:

- **Contamination Control:** Numerous studies report that inadequate use of procedural blanks and poor control of airborne contamination significantly bias particle counts, leading to overestimation (Ma *et al.*, 2024; Al-Mansoori *et al.*, 2025). Strict contamination prevention strategies and procedural blanks are critical for accuracy.
- **Inconsistent Units and Size Definitions:** Reporting conventions vary considerably, with some studies quantifying MPs/NPs as particles per liter, others by mass concentration or polymer percentage composition. Similarly, particle size thresholds differ, disrupting data comparability (Ma *et al.*, 2024; Al-Mansoori *et al.*, 2025).
- **Detection Limit Disparities:** Many investigations do not clearly define or validate detection limits, especially for particles smaller than 1 µm, which are critical for nanoplastic assessment. This inadequacy complicates assessment of abundance and size distributions (Zhang *et al.*, 2024; Al-Mansoori *et al.*, 2025).
- **Matrix Complexity:** Beverage matrices, rich in organic materials, carbonation, and pigments, interfere with digestion procedures and spectral analyses such as micro-FTIR and Raman spectroscopy, reducing detection reliability (Ma *et al.*, 2024; Al-Mansoori *et al.*, 2025).

To progress toward standardized, comparable protocols, future research should focus on:

- **Harmonized Sampling Protocols:** Utilizing non-plastic sampling tools and incorporating rigorous procedural blanks at all processing stages to control contamination (Ma *et al.*, 2024; Al-Mansoori *et al.*, 2025).
- **Dual Analytical Validation:** Combining spectroscopic methods (µ-FTIR, Raman) with polymer-specific mass spectrometry techniques such as pyrolysis-GC/MS or thermal desorption-MS ensures more reliable polymer identification (Zhang *et al.*, 2024; Ma *et al.*, 2024).
- **Standardized Data Reporting:** Mandating comprehensive reporting of detection limits, recovery efficiencies, particle size distribution, and measurement units will promote inter-study comparability and facilitate meta-analyses (Al-Mansoori *et al.*, 2025; Ma *et al.*, 2024).
- **Beverage-Specific Reference Materials:** Developing and deploying certified reference materials tailored to beverage matrices will enable calibration and inter-laboratory validation, enhancing data reproducibility (Ma *et al.*, 2024).

4. Research gaps and priorities

While significant progress has been made, this review highlights several critical gaps that must be addressed to advance the field scientifically and policy-wise:

Nanoplastics quantification and detection: Present analytical capabilities are inadequate for particles less than 100 nm. Investment in ultra-resolution spectroscopic and imaging platforms such as Atomic Force Microscopy-IR (AFM-IR), nanoscale SERS, and coupled AF4-Raman systems is essential.

Beverage production chain tracing: Subsequent research ought to map the complete supply chain from source water to packaging, transportation, and storage to ascertain primary causes of contamination. Life cycle assessments integrating plastic emission hotspots could inform industrial mitigation strategies.

Toxicological and bioavailability assessments.: Few studies have linked beverage-borne MPs/NPs to biological uptake or toxicity. Controlled *in vitro* and *in vivo* models are needed to assess polymer degradation, intestinal absorption, and potential endocrine or inflammatory effects.

Advanced data integration and AI-based detection.: Machine learning and hyperspectral imaging can drastically improve polymer classification, automate particle counting, and reduce human bias. Developing AI-enhanced microplastic image libraries could facilitate cross-laboratory standardization.

Policy-research interface.: Regulatory agencies such as WHO, EFSA, and USEPA must collaborate with analytical scientists to define risk thresholds, exposure guidelines, and acceptable daily intakes for MPs/NPs. Harmonized methods are foundational for such policymaking.

5. Conclusion

Over the past decade, the scientific investigation of microplastics (MPs) and nanoplastics (NPs) in the beverage supply chain has transitioned from anecdotal detection to a rapidly maturing field grounded in analytical chemistry, toxicology, and environmental health. This systematic review synthesized evidence from 42 peer-reviewed studies published between 2020 and 2025, revealing clear methodological trends, persistent inconsistencies, and emerging pathways toward harmonization. The findings demonstrate that microplastic contamination is ubiquitous across all beverage categories examined including bottled water, tea, milk, beer, soft drinks, and plant-based beverages. Concentrations range from tens to tens of thousands of particles per liter, depending on the sampling strategy, beverage type, and analytical method employed. The dominant polymers detected were polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyamide (PA) reflecting their widespread use in packaging, caps, filters, and sealing components. Despite growing awareness, results remain difficult to compare quantitatively due to profound differences in sampling designs, analytical resolutions, contamination control, and data reporting conventions. The lack of standardized protocols continues to impede accurate exposure assessments and the development of regulatory guidelines.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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