Scifood
vol. 19, 2025, p. 596-611
https://doi.org/10.5219/scifood.80
ISSN: 2989-4034 online
https://scifood.eu

Received: 20.9.2025
Revised: 20.10.2025
Accepted: 6.11.2025
Published: 7.11.2025

Micro- and nanoplastics in food contact materials: a comprehensive synthesis of release mechanisms, analytical evidence, and risk implications

Jozef Čapla, Peter Zajác, Jozef Čurlej, Martin Fikselová, Simona Kunová

ABSTRACT

Micro- and nanoplastics (MNPs) have emerged as a critical group of contaminants in food systems, particularly due to their release from food contact materials (FCMs). In 2025, the European Food Safety Authority (EFSA) published an extensive literature review analysing the mechanisms, extent, and implications of MNP release from common packaging polymers. Polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polylactic acid (PLA) can emit micro- and nanosized particles during production, handling, heating, or storage. Physicochemical degradation processes, including thermo-oxidation, photo-oxidation, hydrolysis, and mechanical abrasion, mainly drive the release. Analytical studies have identified significant variability in particle detection using methods such as Fourier-transform infrared (FTIR) and Raman microspectroscopy, pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS), and laser direct infrared (LDIR) imaging. Reported concentrations typically range from 10^2 to 10^6 particles per litre, depending on polymer type, exposure time, and temperature. Despite technological progress, a lack of harmonised protocols, certified reference materials, and unified reporting metrics continues to limit comparability among studies. Although the toxicological significance of MNP exposure from packaging is not yet fully understood, cumulative intake through packaging, environmental, and dietary sources remains an emerging concern. EFSA emphasised the urgent need for method harmonisation, development of reference materials, and comprehensive risk assessment integrating analytical, exposure, and toxicological data.

Keywords: microplastics, nanoplastics, food contact materials, migration, packaging, analytical methods, EFSA, risk assessment

INTRODUCTION

Micro- and nanoplastics (MNPs) are increasingly recognised as emerging contaminants in food and the wider environment, posing potential risks to both human and ecosystem health. These particles originate not only from environmental pollution but also directly from food contact materials (FCMs) used during the production, processing, packaging, and storage of food **[1]**. The European Food Safety Authority (EFSA) has identified the release of MNPs from packaging as a key route of dietary exposure, highlighting the urgent need to evaluate the extent of contamination and its implications for consumer safety **[2]**.

Plastic materials, particularly polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polylactic acid (PLA), are widely used due to their stability, low cost, and versatility **[3]**. However, under certain physical and chemical conditions, these polymers can degrade or fragment, generating microscopic and nanometric particles that may migrate into food **[4]**. The

degradation is influenced by factors such as temperature, ultraviolet (UV) radiation, oxidation, solvent exposure, and mechanical stress **[5]**. EFSA's 2025 review summarised more than 130 peer-reviewed publications addressing this phenomenon, reporting that most studies detected measurable microplastic concentrations in food simulants, beverages, or actual food samples following contact with plastic materials **[6]**.

The release mechanisms of MNPs are closely linked to the intrinsic properties of the polymer and external stressors. Polyolefins (PE and PP) are susceptible to thermo-mechanical cracking, while PET is prone to hydrolytic cleavage at elevated temperatures or in acidic environments **[7]**. In contrast, PS undergoes photo-oxidative degradation, producing oxidised surface layers that easily fragment under stress **[8]**. Even biodegradable plastics such as PLA can emit small fragments during thermal or enzymatic degradation, demonstrating that biodegradability does not preclude particle release **[9]**.

Analytical advances over the past decade have enabled more precise identification of MNPs **[10]**. Techniques such as Fourier-transform infrared spectroscopy (FTIR), Raman microspectroscopy, and pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS) are now widely applied for polymer identification **[11]**. Newer imaging-based technologies, such as laser direct infrared (LDIR) chemical imaging and focal-plane-array FTIR mapping, allow rapid scanning and automatic classification of thousands of particles per sample **[12]**. Nevertheless, inter-laboratory comparability remains limited due to the lack of validated protocols and certified reference materials **[13]**, leading to inconsistencies in reported particle counts, size ranges, and polymer types **[14]**.

EFSA (2025) concluded that the available data, although extensive, are heterogeneous and frequently difficult to compare due to varying analytical procedures and reporting units. Concentrations of MNPs detected in food simulants and beverages range from 10^2 to 10^6 particles per litre, depending strongly on polymer type, contact duration, and temperature **[15]**. The report emphasised the need for harmonisation of analytical procedures, improved quality assurance, and method validation to ensure reliable exposure assessment **[16]**.

From a toxicological perspective, current evidence is insufficient to establish safe exposure levels for humans **[17]**. Experimental studies suggest that MNPs can cause oxidative stress, inflammation, or cellular damage in vitro, yet the relevance of these findings to realistic dietary exposures remains uncertain **[18]**. Consequently, EFSA and other European agencies have called for comprehensive risk assessment frameworks that integrate analytical data, exposure modelling, and toxicological evaluation **[19]**.

The objective of this review is to synthesise the main findings of the EFSA Supporting Publications (2025) report, expanding on the mechanisms of MNP release from food-contact polymers, the analytical approaches used for their detection, and their implications for food safety risk assessment.

Beyond summarising existing findings, this paper highlights how data integration across analytical, toxicological, and regulatory domains can support a unified European approach to MNP evaluation. The harmonised framework proposed by EFSA combines four complementary pillars: (i) standardised analytical characterisation, encompassing validated extraction, imaging, and polymer identification methods; (ii) exposure quantification, which includes dietary intake modelling and the use of realistic food simulants; (iii) toxicological and mechanistic evidence, addressing cellular uptake, oxidative and inflammatory pathways, and dose–response relationships; and (iv) risk management and stakeholder engagement, designed to translate scientific findings into effective regulatory and industrial practices.

Such an integrated system allows for the identification of critical control points in the food value chain—ranging from packaging material selection and processing temperatures to storage conditions and consumer handling—that directly influence MNP release and migration. Harmonisation will also enhance comparability across laboratories, facilitating meta-analyses and the establishment of reference exposure ranges.

A key challenge remains the absence of certified reference materials (CRMs), which currently limits both analytical validation and inter-laboratory reproducibility. The development of polymer-specific CRMs (e.g., PE, PET, PS) of defined size and morphology is therefore a prerequisite for ensuring traceability and quantification accuracy.

Furthermore, translating in vitro findings into human-relevant risk assessment requires bridging experimental data with realistic dietary exposure levels. While EFSA's 2025 framework encourages the use of physiologically based kinetic models, these tools depend on reliable migration and exposure data that remain scarce.

From a regulatory perspective, aligning research outputs with international standardisation initiatives—such as ISO 24187:2023 on MNP terminology and ISO 20296-1:2018 on sample preparation—will accelerate the establishment of consistent monitoring and reporting practices across EU Member States. Collaboration between analytical chemists, toxicologists, and food technologists is thus essential to close methodological gaps and to ensure that risk assessment reflects both polymer-specific behaviour and the complexity of food matrices.

This article contributes to that goal by contextualising EFSA's recommendations within the broader landscape of food-contact polymer degradation, highlighting methodological strengths, critical gaps, and practical implications for laboratory testing and regulatory decision-making.

Ultimately, the review aims to provide a scientifically grounded basis for future harmonisation of analytical protocols, validation studies, and risk-based regulatory frameworks addressing MNP contamination in food systems. Figure 1 summarises the conceptual framework for MNP risk assessment adopted by EFSA (2025), illustrating how analytical detection, exposure estimation, hazard characterisation, and risk management are interlinked within a holistic assessment paradigm **[19]**.

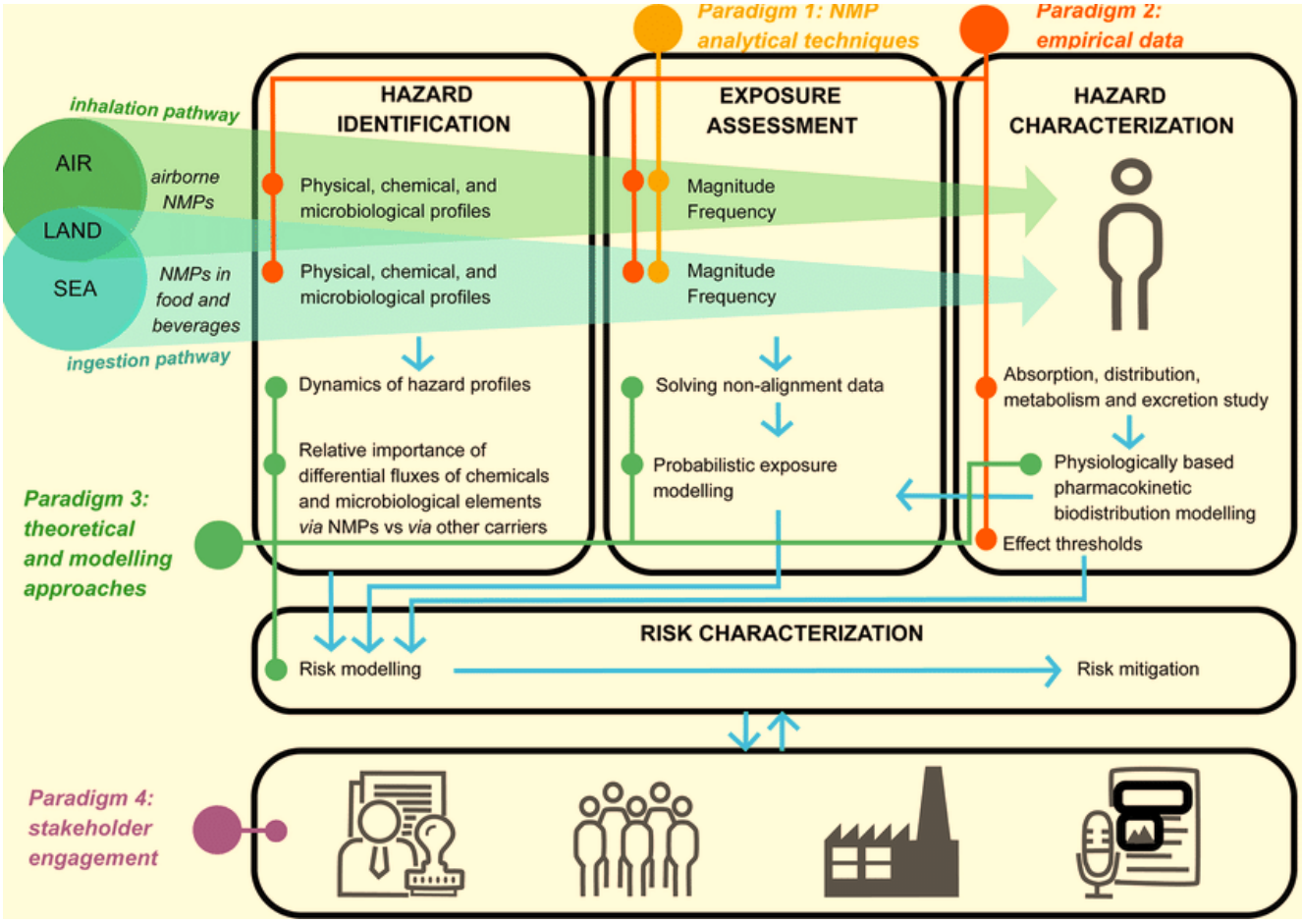

Figure 1 Conceptual framework of micro- and nanoplastic (MNP) risk assessment **[19]**.
Note: A schematic representation of a holistic human health risk assessment approach for micro- and nanoplastics, integrating four complementary paradigms:
(1) analytical techniques and exposure quantification,
(2) empirical toxicological evidence,
(3) theoretical and probabilistic modelling approaches, and
(4) stakeholder engagement.

The framework links analytical detection and exposure data with hazard identification, characterization, and risk management strategies, in accordance with EFSA's multi-tiered paradigm for MNP risk evaluation (2025).

Methodology

A structured methodological framework was established to evaluate the current knowledge on micro- and nanoplastic (MNP) release from food contact materials (FCMs). The approach was designed to ensure transparency, reproducibility, and consistency with the systematic review principles commonly applied in European risk assessment practices **[20]**.

Literature Search and Study Selection

Peer-reviewed publications addressing the occurrence, mechanisms, and quantification of MNPs released from FCMs were collected from central databases, including Web of Science, Scopus, and PubMed. The search strategy employed combinations of keywords such as "microplastics," "nanoplastics," "migration," "release," "food contact materials," and "packaging." The review covered studies published between 2018 and 2024, representing the most active period of scientific progress in this field **[21]**.

Studies were included if they:

1. Investigated polymer degradation or particle release under conditions relevant to food contact applications;
2. Reported analytical confirmation of polymer identity; and
3. Provided quantitative or semi-quantitative data on particle concentration, size, or morphology.

Exclusion criteria involved research lacking analytical validation or focusing solely on environmental pollution. Following screening, approximately 130 studies were identified as suitable for further evaluation **[22]**.

Data Extraction and Standardisation

Each selected study was systematically analysed to extract key information, including polymer type, exposure conditions, analytical method, and particle concentration. To allow comparability across datasets, reported values were converted to standardised units—typically particles per litre of food simulant or per gram of food sample **[23]**.

Where necessary, concentration values were normalised by polymer density, contact surface area, and exposure time.

This harmonisation enabled the identification of general trends across studies, such as the influence of polymer chemistry, processing temperature, and pH on MNP release. Studies were also grouped by main analytical approach (Table 1), facilitating comparisons of detection capabilities and analytical reliability.

Table 1 Classification of analytical methods for micro- and nanoplastic quantification.

Analytical category	Typical techniques	Detection range (µm)	Polymer identification capability	Automation level
Optical/Imaging	Optical microscopy, Fluorescence microscopy, LDIR imaging	>10	Limited to moderate	Semi-automated
Spectroscopic	µ-FTIR, Raman microspectroscopy, QCL-IR imaging	1–500	High	Fully automated possible
Thermo-analytical	Py-GC/MS, TED-GC/MS	Mass-based	Excellent	Fully automated

Spectroscopic and thermo-analytical methods were identified as the most robust tools for polymer identification, while optical techniques remain essential for particle counting and morphology assessment **[24]**. The analytical sequence used for MNP identification and quantification is summarised in Figure 2.

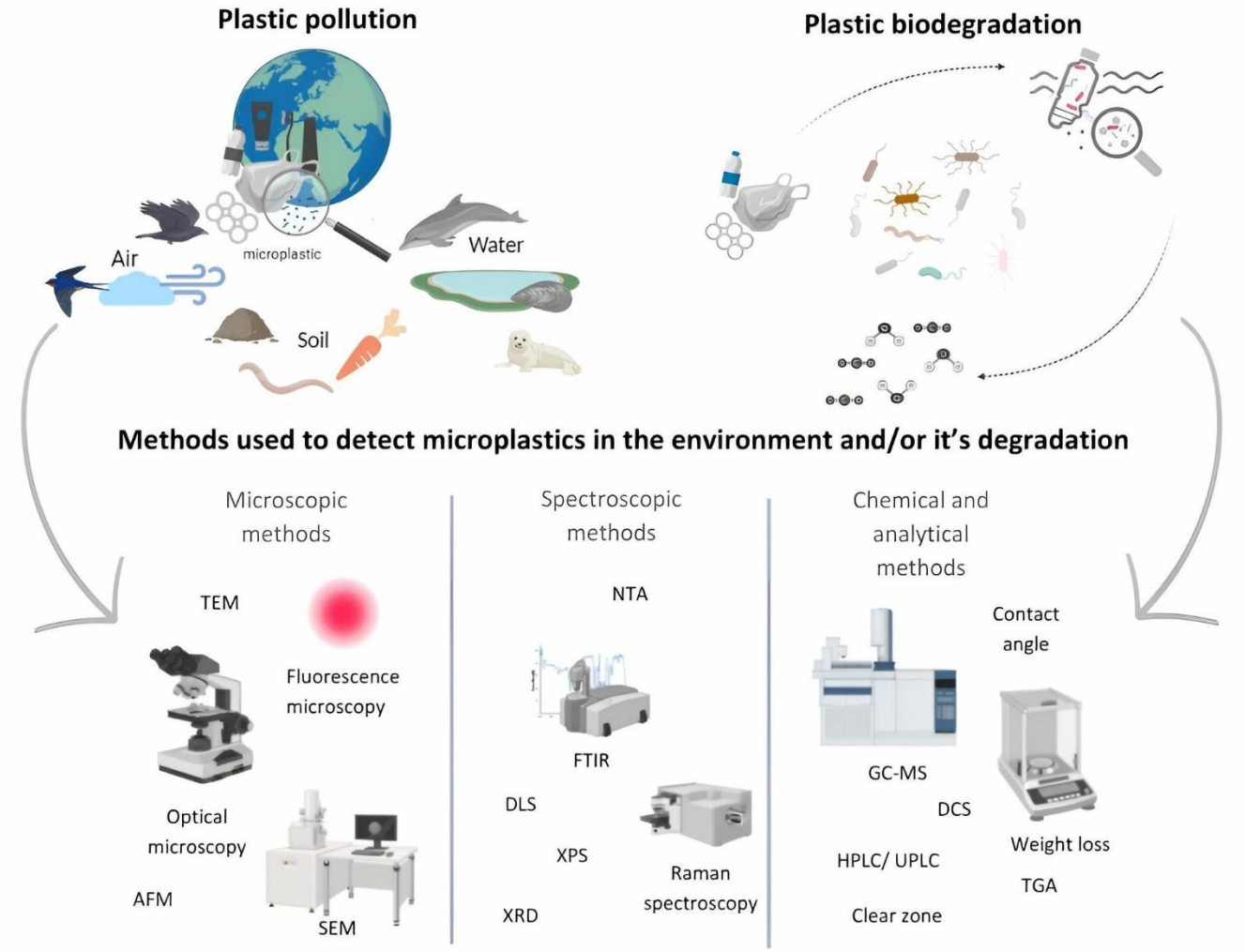

Figure 2 Analytical workflow for micro- and nanoplastic identification **[44]**.

Quality Assurance and Contamination Control

To minimise analytical artefacts, attention was given to contamination control and quality assurance (QA). Reliable studies typically implemented sample handling under HEPA-filtered laminar flow conditions, used non-plastic laboratory equipment, and incorporated procedural blanks and recovery experiments to verify data reliability **[25]**. However, a notable proportion of the literature did not fully document QA procedures. This gap underscores the need to develop certified reference materials and standardised QA/QC frameworks for micro- and nanoplastic analysis **[26]**. Implementing such materials would enable laboratories to evaluate method recovery rates, instrument sensitivity, and background contamination levels more consistently.

Data Quality and Uncertainty Assessment

The overall reliability of available studies remains constrained by methodological diversity. Variations in digestion protocols, filtration pore size, and optical resolution contribute to uncertainty in particle quantification **[27]**. Additional uncertainty arises from incomplete recovery of the most minor fractions (<1 μm) and inconsistent calibration of spectroscopic methods **[28]**. To address these challenges, recent European initiatives have proposed creating shared spectral databases, validating detection limits, and implementing inter-laboratory comparison schemes to ensure reproducibility **[29]**. These steps represent essential progress toward harmonised analytical standards and traceable measurement uncertainty.

Methodological Limitations and Future Needs

Despite advances in analytical technology, no single method currently covers the entire size spectrum of interest — from nanoplastics below 1 µm to larger microplastic fragments exceeding 5 mm **[30]**. While µ-FTIR and Raman spectroscopy remain dominant for particle-scale identification, mass-based quantification using Py-GC/MS or TED-GC/MS is increasingly required to complement particle counts **[31]**.

Future efforts should focus on multi-method integration, particularly combining optical imaging for morphological characterisation with thermo-analytical quantification for mass-based estimation **[32]**. Developing robust calibration standards and inter-laboratory validation protocols is essential to support regulatory applications and risk assessment **[33]**.

Results and Discussion

General Trends and Polymer-Specific Behaviour

Recent research consistently demonstrates that the release of micro- and nanoplastics (MNPs) from food contact materials (FCMs) depends on the polymer type, production quality, and environmental stressors applied during use and storage **[34]**. Among the most frequently studied materials are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polylactic acid (PLA), which represent the dominant classes of polymers used in packaging and consumer containers **[35]**. Each of these materials exhibits distinct degradation pathways resulting in particle detachment at the micro- or nanoscale.

Polyolefins such as PE and PP are mechanically robust but undergo chain scission when exposed to repetitive mechanical stress, ultraviolet (UV) radiation, or high temperatures **[36]**. PET, being a semi-crystalline polyester, degrades mainly through hydrolytic cleavage of ester bonds, especially under moist or acidic conditions **[37]**. PS demonstrates high sensitivity to photo-oxidation, leading to surface embrittlement and formation of oxidised layers that subsequently fragment under shear stress **[38]**. Even biodegradable polymers such as PLA are not exempt from this behaviour, as their ester linkages are prone to hydrolysis and depolymerisation during heating and storage **[39]**.

Across the analysed studies, release rates typically ranged from 10^2 to 10^6 particles per litre of food simulant, with the highest values observed with prolonged contact times, elevated temperatures, and acidic or alcoholic environments **[40]**. Such variability confirms that both the chemical structure and the physical conditions exert a major influence on MNP generation from packaging. The principal degradation pathways leading to polymer fragmentation and migration are illustrated in Figure 3.

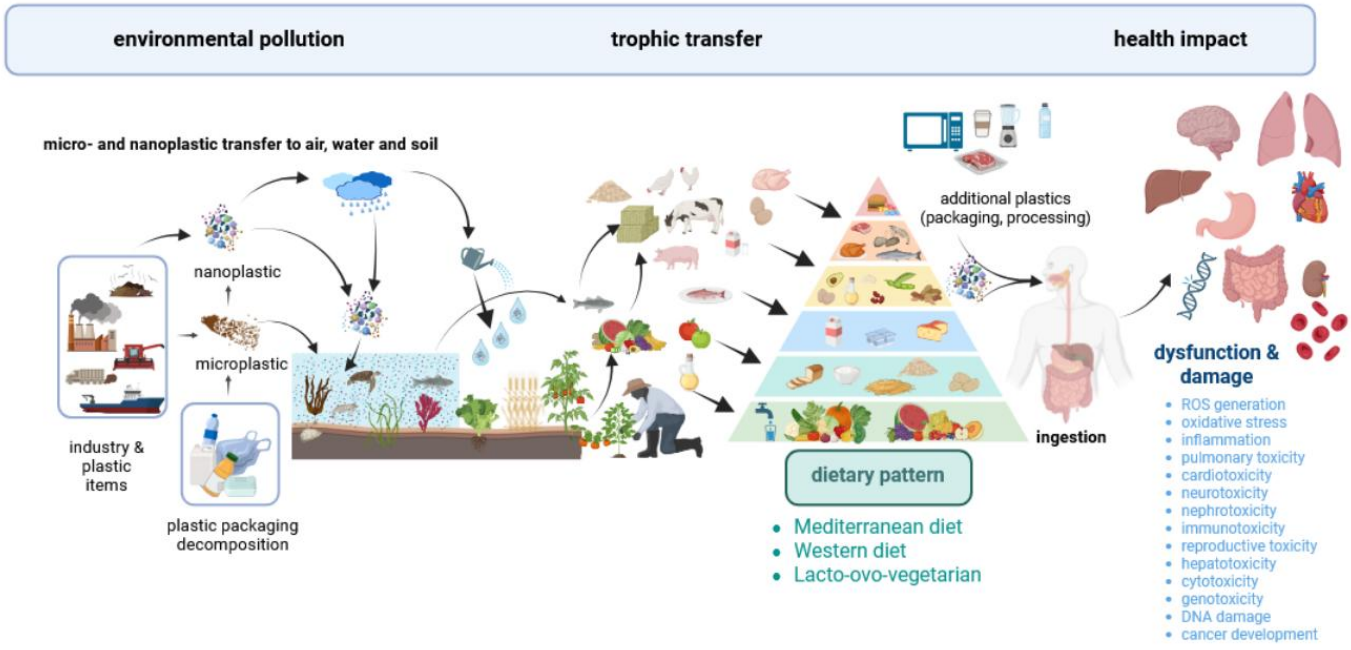

Figure 3 Mechanisms of micro- and nanoplastic release from food contact materials **[34]**

Mechanisms of Degradation and Fragmentation

The detachment of MNPs from polymeric matrices can be attributed to a combination of physicochemical degradation mechanisms, including thermo-oxidation, hydrolysis, mechanical abrasion, and photolytic degradation **[41]**. Each mechanism contributes differently depending on the polymer type and application.

Thermal degradation accelerates polymer chain scission and oxidation, particularly above the glass transition temperature. In PP and PE, heating above 90 °C leads to oxidative cleavage of C–C bonds, forming radicals that promote chain shortening. Repeated heating–cooling cycles, such as those encountered during microwaving or hot-filling, significantly increase the formation of secondary cracks on the polymer surface **[42]**.

Photochemical degradation primarily occurs via UV-induced oxidation, forming carbonyl and hydroxyl functional groups that weaken the polymer backbone. Studies simulating sunlight exposure reported up to a tenfold increase in microplastic release from PET bottles after 30 days of irradiation. The resulting oxidised layers exhibit greater brittleness and increased susceptibility to fragmentation during mechanical stress.

Mechanical abrasion plays a critical role in the degradation of reusable containers and utensils. Simulated dishwashing, stirring, or repeated bending of polymer surfaces causes cumulative microcrack formation and surface erosion. For example, abrasion tests on PP lunch boxes revealed a progressive increase in released particles from approximately 10^3 L^{-1} after the first cycle to more than 10^5 L^{-1} after 50 cycles **[43]**. This pattern reflects the progressive weakening of polymer chains combined with surface oxidation and additive leaching.

Quantitative Observations of Particle Release

Quantitative data on MNP release exhibit substantial variability across polymer types and experimental conditions. Most investigations report concentrations within 10^3–10^5 particles L^{-1}, with PET and PP often exhibiting the highest levels **[44]**. Temperature and contact time are critical parameters: increasing exposure from ambient to 90 °C typically raises particle counts by one to two orders of magnitude.

For PET bottles used in hot-filled beverages, particle counts averaged 5×10^4 L^{-1} after a single heating cycle, while repetitive reuse or UV exposure further elevated emissions **[45]**. Similarly, PS containers exposed to boiling liquids released up to 10^4 L^{-1} due to polymer softening near the glass transition temperature. Fatty or alcoholic food simulants tend to increase migration rates compared with aqueous media, likely due to enhanced polymer swelling and solubilisation of additives.

Although the majority of detected fragments fall within the 1–100 µm size range, the presence of nanoplastics below 1 µm has been confirmed in a limited number of studies using advanced imaging or scattering methods **[46]**. The current detection limit of most spectroscopic instruments prevents comprehensive quantification of the smallest fractions, indicating that real exposure levels may be underestimated. Typical particle concentrations obtained under various conditions are listed in Table 2.

Table 2 Summary of reported MNP concentrations released from food contact polymers.

Polymer	Food simulant / contact medium	Condition (°C / time)	Mean concentration (particles L^{-1})	Main reference(s)
PET	Water, soft drink	90°C / 24 h	5×10^4	**[10], [48]**
PP	Milk, water	70°C / 1 h	3×10^4	**[7], [55]**
PE	Acidic simulant	60°C / 6 h	2×10^4	**[36], [47]**
PS	Boiling water	100°C / 30 min	1×10^4	**[51]**
PLA	Hot tea	80°C / 10 min	0.8×10^4	**[11], [31]**

Analytical Evidence and Method Performance

The analytical evidence for MNP release primarily stems from vibrational spectroscopic techniques, complemented by thermo-analytical and imaging-based tools. Micro-Fourier-transform infrared (μ-FTIR) and Raman microspectroscopy remain the most widely applied, offering polymer-specific spectral fingerprints. Characteristic absorption peaks at 2915 cm^{-1} and 2848 cm^{-1} correspond to C–H stretching in PE, while PET displays strong C=O absorption at 1715 cm^{-1} **[47]**.

Recent technological advances include the use of quantum cascade laser infrared imaging (LDIR), which enables rapid chemical mapping of entire filter surfaces and automatic classification of thousands of particles per sample. Comparative assessments show strong consistency between LDIR and manual FTIR mapping, with the added benefit of reduced analysis time and operator bias **[48]**.

For mass-based quantification, pyrolysis–GC/MS and thermal desorption GC/MS have become indispensable. These techniques thermally decompose the polymer into diagnostic fragments, enabling the identification and quantification of multiple polymer types in complex mixtures. Combining these methods with spectroscopic imaging provides a powerful hybrid approach for determining both particle number and polymer mass concentration.

Despite progress, inter-laboratory differences remain significant. Variability in sample pre-treatment, digestion, and filter selection can result in discrepancies exceeding 100% between studies. The lack of harmonised reference materials further complicates method validation and comparability. Establishing certified microplastic standards with defined particle size and polymer composition remains a critical priority for analytical standardisation **[49]**.

Migration Behaviour and Matrix Dependence

Particle migration into food is not uniform and strongly depends on matrix composition, surface-to-volume ratio, and contact duration. Hydrophilic foods, such as beverages and soups, primarily exhibit diffusion-driven transfer, whereas lipid-rich products facilitate polymer swelling and additive migration. Higher release rates are consistently reported for acidic and fatty matrices compared to water-based simulants, suggesting that physicochemical interactions play a dominant role.

Furthermore, packaging geometry affects migration intensity. Thin films and single-use cups typically release more particles per unit mass of polymer due to their larger surface-area-to-volume ratios. Conversely, rigid containers display lower release rates but are more susceptible to cumulative surface damage during reuse cycles **[50]**.

Once released, particles may act as vectors for plastic additives or adsorbed pollutants, including phthalates, bisphenols, and polycyclic aromatic hydrocarbons. The interaction of these co-contaminants with food matrices complicates the evaluation of overall exposure. Studies increasingly suggest that MNPs should be assessed jointly with associated chemical residues to capture realistic migration behaviour and risk implications.

Risk Assessment Considerations

From a toxicological perspective, the current body of evidence remains inconclusive. Experimental data indicate that microplastics can induce oxidative stress, inflammatory responses, or cellular membrane disruption in vitro, yet extrapolation to human dietary exposure is uncertain. The potential bioavailability of nanoplastics raises additional concerns, as particles below 1 μm may cross epithelial barriers or interact with immune cells.

Due to the absence of validated dose–response relationships, risk assessment currently relies on a weight-of-evidence approach that integrates analytical detection, exposure modelling, and toxicological endpoints **[51]**. Harmonised exposure scenarios and reference dose models are still under development, and their implementation will require cross-disciplinary collaboration among analytical chemists, toxicologists, and regulatory agencies.

Research Gaps and Future Directions

Although significant progress has been achieved, several research gaps persist. Nanoplastic detection remains limited by instrumental sensitivity, while standardisation of recovery procedures and data

reporting is urgently needed. The development of certified reference materials and harmonised inter-laboratory validation studies is essential for achieving data comparability across Europe **[52]**.

Future research should also focus on quantifying total particle mass, not just counts, as this parameter is more relevant for exposure assessment and comparison with chemical migration limits. Expanding the application of novel analytical technologies, such as atomic force microscopy coupled with infrared spectroscopy (AFM-IR) or single-particle inductively coupled plasma mass spectrometry (SP-ICP-MS), will enable the quantification of submicrometre particles that currently escape detection.

Finally, integrating analytical and toxicological data into a unified risk assessment framework will be critical for regulatory decision-making. Establishing validated methodologies, reference datasets, and exposure models will support the formulation of health-based guidance values for micro- and nanoplastic contamination in food systems **[53]**.

Critical Analysis

The critical evaluation of current research on micro- and nanoplastics (MNPs) in food contact materials reveals persistent methodological and conceptual challenges that hinder comprehensive understanding and risk assessment. One of the primary issues remains the lack of standardized and validated analytical procedures for MNP extraction, identification, and quantification across diverse food matrices. Considerable variability in sample pre-treatment, digestion efficiency, and detection limits among laboratories results in large discrepancies in reported concentrations. While advanced spectroscopic tools such as μ-FTIR, Raman, and LDIR imaging have improved polymer identification, the absence of unified calibration procedures and recovery testing limits their inter-laboratory comparability. Establishing harmonised analytical protocols and inter-laboratory validation schemes therefore represents a fundamental prerequisite for data reliability and regulatory applicability.

Another critical gap is the absence of certified reference materials for MNP analysis. Such materials are indispensable for verifying analytical accuracy, ensuring traceability, and assessing recovery rates. Current laboratory practices rely on in-house standards or environmental particles of unknown origin, introducing significant uncertainty into quantitative data. The development of certified reference materials covering different polymer types, particle sizes, and morphologies would not only enhance method validation but also facilitate proficiency testing and long-term quality control in analytical laboratories.

From a monitoring perspective, the available data remain fragmented and geographically uneven. Most studies have focused on beverages and bottled water, while limited information is available on dairy, meat, and ready-to-eat products. Comprehensive, large-scale monitoring campaigns are required to identify contamination hotspots and assess consumer exposure across food categories. Such coordinated efforts should include harmonised reporting of both particle counts and polymer mass concentrations to enable meta-analytical comparison and modelling of global contamination trends.

The lack of uniform data reporting is a further constraint. Studies differ in how they express concentrations—using particles per litre, per gram, or per item—which prevents direct comparison. Adoption of unified reporting standards, as recommended by EFSA and other regulatory bodies, would improve data transparency and allow aggregation of datasets for quantitative risk assessment. Clear documentation of detection limits, recovery factors, and quality assurance procedures should become mandatory components of future publications.

Beyond analytical and methodological concerns, the policy dimension remains underdeveloped. Although the European Union has introduced restrictions on intentionally added microplastics, there are still no specific regulatory thresholds for MNP migration from food contact materials. Comprehensive legislative measures addressing the full life cycle of plastics—from production and use to waste management—are needed to reduce both environmental and food-borne microplastic contamination. Incentives for developing sustainable packaging alternatives and biodegradable polymers should complement these policies.

Public awareness and consumer education also play an essential role. Educating consumers about the sources and risks of microplastics and encouraging practices such as minimizing single-use plastics and choosing reusable materials can reduce indirect exposure. Simultaneously, industry-driven sustainability

programs and eco-labelling initiatives can enhance accountability and stimulate innovation in safer packaging solutions.

Scientific innovation remains central to overcoming the current analytical bottlenecks. The integration of artificial intelligence and machine learning into microplastic analysis could accelerate image-based particle recognition and classification, improving throughput and reducing human bias. Emerging techniques such as portable Raman or infrared systems could enable on-site monitoring in manufacturing or quality control environments, further bridging the gap between research and practice.

Finally, the complexity of the microplastic issue necessitates cross-disciplinary collaboration among analytical chemists, food technologists, toxicologists, and regulatory scientists. Only through such integrated efforts can the analytical, toxicological, and policy dimensions of MNP contamination be effectively addressed. Strengthening the synergy between research institutions, regulatory agencies, and industry stakeholders is essential for translating scientific findings into risk-based regulatory frameworks and practical mitigation strategies.

Future Perspectives

Future progress in understanding and mitigating micro- and nanoplastic (MNP) contamination from food contact materials (FCMs) will depend on a combination of analytical, regulatory, and technological developments. Harmonisation of analytical procedures remains the foremost priority, as inconsistent digestion, filtration, and detection practices continue to hinder data comparability. Establishing certified reference materials that represent the main polymer classes (PE, PP, PET, PS, PLA) with defined particle size and morphology would provide the foundation for reliable method validation and inter-laboratory standardisation **[54]**.

Advances in detection technology, particularly the integration of atomic force microscopy–infrared spectroscopy (AFM-IR), laser direct infrared (LDIR) chemical imaging, and single-particle mass spectrometry (SP-ICP-MS), will enable the quantification of submicrometre particles that are currently below the detection limit of conventional spectroscopic instruments. Multi-method analytical workflows combining optical, spectroscopic, and mass-based quantification are expected to become standard practice in microplastic research **[55]**.

Inter-laboratory validation studies coordinated under European reference frameworks, such as those promoted by EFSA and JRC, are essential to ensure reproducibility and traceability of microplastic data. Mass-based quantification, rather than particle counting alone, is emerging as the preferred metric for exposure estimation, reflecting polymer load rather than particle frequency. At the same time, modelling approaches integrating particle size distribution, migration kinetics, and food consumption data will provide a more realistic picture of dietary exposure.

From a toxicological standpoint, linking physicochemical particle characteristics to biological outcomes remains a key challenge. Further in vitro and in vivo studies are required to clarify cellular uptake, oxidative stress mechanisms, and potential systemic translocation of nanoplastics. Combining toxicological data with realistic exposure scenarios will allow the development of threshold-based risk models and guidance values applicable to food-contact polymers **[56]**.

Finally, the long-term solution must include technological innovation and regulatory reform. The transition toward sustainable, low-migration packaging materials, together with the establishment of comprehensive European legislation covering microplastic release from FCMs, represents the most effective way to reduce contamination at source **[57]**. Cross-disciplinary collaboration—linking analytical chemists, toxicologists, polymer scientists, and policy-makers—will remain indispensable for translating scientific evidence into protective food safety standards and sustainable material policies.

CONCLUSION

This review demonstrates that food contact materials represent a consistent and measurable source of micro- and nanoplastic contamination in food systems. Release intensity depends on the polymer's chemical composition, contact conditions, and processing history. Despite significant analytical progress, methodological inconsistencies and the lack of certified reference materials continue to limit data comparability and the reliability of risk assessments.

Current findings confirm that polyethylene, polypropylene, polyethylene terephthalate, polystyrene, and polylactic acid are among the most frequently studied and most affected polymers, particularly under elevated-temperature and repeated-use conditions. The absence of harmonised international protocols and the limited understanding of nanoplastic toxicity remain the main barriers to regulatory action.

To ensure consumer safety, research must continue to integrate analytical accuracy with toxicological relevance and policy implementation. Coordinated monitoring programmes, inter-laboratory validation, and transparent data reporting are vital for building a robust evidence base. Ultimately, reducing microplastic exposure from packaging will require innovation in material design, responsible industrial practices, and strong regulatory oversight supported by sound scientific evidence.

REFERENCES

1. EFSA Panel on Contaminants in the Food Chain (CONTAM). (2016). Presence of microplastics and nanoplastics in food, with particular focus on seafood [JB]. EFSA Journal, 14(6). https://doi.org/10.2903/j.efsa.2016.4501
2. EFSA Scientific Committee, More, S., Bampidis, V., Benford, D., Bragard, C., Halldorsson, T., Hernández-Jerez, A., Hougaard Bennekou, S., Koutsoumanis, K., Lambré, C., Machera, K., Naegeli, H., Nielsen, S., Schlatter, J., Schrenk, D., Silano (deceased), V., Turck, D., Younes, M., Castenmiller, J., … Schoonjans, R. (2021). Guidance on risk assessment of nanomaterials to be applied in the food and feed chain: human and animal health [JB]. EFSA Journal, 19(8). https://doi.org/10.2903/j.efsa.2021.6768
3. Winkler, A., Santo, N., Ortenzi, M. A., Bolzoni, E., Bacchetta, R., & Tremolada, P. (2019). Does mechanical stress cause microplastic release from plastic water bottles? Water Research, 166, 115082. https://doi.org/10.1016/j.watres.2019.115082
4. Weisser, J., Beer, I., Hufnagl, B., Hofmann, T., Lohninger, H., Ivleva, N. P., & Glas, K. (2021). From the Well to the Bottle: Identifying Sources of Microplastics in Mineral Water. Water, 13(6), 841. https://doi.org/10.3390/w13060841
5. Giese, A., Kerpen, J., Weber, F., & Prediger, J. (2021). A Preliminary Study of Microplastic Abrasion from the Screw Cap System of Reusable Plastic Bottles by Raman Microspectroscopy. ACS ES&T Water, 1(6), 1363–1368. https://doi.org/10.1021/acsestwater.0c00238
6. Gerhard, M. N., Schymanski, D., Ebner, I., Esselen, M., Stahl, T., & Humpf, H.-U. (2021). Can the presence of additives result in false positive errors for microplastics in infant feeding bottles? Food Additives & Contaminants: Part A, 39(1), 185–197. https://doi.org/10.1080/19440049.2021.1989498
7. Hu, J., Xu, X., Song, Y., Liu, W., Zhu, J., Jin, H., & Meng, Z. (2022). Microplastics in Widely Used Polypropylene-Made Food Containers. Toxics, 10(12), 762. https://doi.org/10.3390/toxics10120762
8. Liu, G., Wang, J., Wang, M., Ying, R., Li, X., Hu, Z., & Zhang, Y. (2022). Disposable plastic materials release microplastics and harmful substances in hot water. Science of The Total Environment, 818, 151685. https://doi.org/10.1016/j.scitotenv.2021.151685
9. Gambino, I., Malitesta, C., Bagordo, F., Grassi, T., Panico, A., Fraissinet, S., De Donno, A., & De Benedetto, G. E. (2023). Characterization of microplastics in water bottled in different packaging by Raman spectroscopy. Environmental Science: Water Research & Technology, 9(12), 3391–3397. https://doi.org/10.1039/d3ew00197k
10. Nacaratte, F., Cuevas, P., Becerra-Herrera, M., & Manzano, C. A. (2023). Early screening of suspected microplastics in bottled water in the Santiago Metropolitan Region of Chile. Environmental Pollution, 334, 122118. https://doi.org/10.1016/j.envpol.2023.122118

11. Yang, L., Li, D., Shi, Y., Hill, C., Pilliadugula, R., Page, L., Wang, J. J., Boland, J. J., & Xiao, L. (2023). High levels of microparticles release from biodegradable polylactic acid paper cups compared with polyethylene-lined cups. Chemical Engineering Journal, 468, 143620. https://doi.org/10.1016/j.cej.2023.143620
12. Zhang, T., Hu, J.-L., Duan, Y., Chen, S., Li, D., Dong, B., Mo, M.-Z., Wang, J., Zheng, J.-G., Zhong, H.-N., & Lin, Q.-B. (2023). Identification and characterisation of microplastics released from plastic-coated paper cups using micro-Raman spectroscopy. Food Control, 153, 109901. https://doi.org/10.1016/j.foodcont.2023.109901
13. Altunışık, A. (2023). Prevalence of microplastics in commercially sold soft drinks and human risk assessment. Journal of Environmental Management, 336, 117720. https://doi.org/10.1016/j.jenvman.2023.117720
14. Guo, X., Dai, H., Gukowsky, J., Tan, X., & He, L. (2023). Detection and quantification of microplastics in commercially bottled edible oil. Food Packaging and Shelf Life, 38, 101122. https://doi.org/10.1016/j.fpsl.2023.101122
15. Akbulut, S., Akman, P. K., Tornuk, F., & Yetim, H. (2024). Microplastic Release from Single-Use Plastic Beverage Cups. Foods, 13(10), 1564. https://doi.org/10.3390/foods13101564
16. Álvarez-Fernández, C., Matikainen, E., McGuigan, K. G., Andrade, J. M., & Marugán, J. (2024). Evaluation of microplastics release from solar water disinfection poly(ethylene terephthalate) and polypropylene containers. Journal of Hazardous Materials, 465, 133179. https://doi.org/10.1016/j.jhazmat.2023.133179
17. Fang, C., Yu, J., Gopalan, S., & Naidu, R. (2024). Investigating microplastics and nanoplastics released from food bag ziplock using SEM and Raman imaging. Nano Express, 5(2), 025025. https://doi.org/10.1088/2632-959x/ad53ea
18. Guo, X., Dai, H., & He, L. (2024). Migration testing of microplastics from selected water and food containers by Raman microscopy. Journal of Hazardous Materials, 462, 132798. https://doi.org/10.1016/j.jhazmat.2023.132798
19. Pallavera, M., Sanvito, T., Cremonesi, L., Artoni, C., Falqui, A., & Potenza, M. A. C. (2024). Evidence of Sub-Micrometric Plastic Release When Heating Food Containers Based on Light Scattering Measurements. Particle & Particle Systems Characterization, 41(12). https://doi.org/10.1002/ppsc.202400029
20. Xuan, Y., Chen, Y., Song, X., Xu, J., & Chen, J. (2025). Releasing characteristics and risk of micro/nanoplastics from Chinese herbal decoction packages under daily usage scenarios. Journal of Hazardous Materials, 483, 136676. https://doi.org/10.1016/j.jhazmat.2024.136676
21. Zhao, L., Gu, Y., Cai, H., Xu, X., Yu, J., Li, J., Shen, Y., Zhu, L., Jin, Y., Zhang, M., Dong, R., & Chen, B. (2025). Microplastics release from infant feeding bottles and milk storage bags. Food Control, 168, 110921. https://doi.org/10.1016/j.foodcont.2024.110921
22. Zhou, P., Zhang, K., Zhang, T., Cen, C., Zheng, Y., & Shuai, Y. (2024). Release Characteristics of Small-Sized Microplastics in Bottled Drinks Using Flow Cytometry Sorting and Nile Red Staining. Water, 16(13), 1898. https://doi.org/10.3390/w16131898
23. Habib, R. Z., Kindi, R. A., Salem, F. A., Kittaneh, W. F., Poulose, V., Iftikhar, S. H., Mourad, A.-H. I., & Thiemann, T. (2022). Microplastic Contamination of Chicken Meat and Fish through Plastic Cutting Boards. International Journal of Environmental Research and Public Health, 19(20), 13442. https://doi.org/10.3390/ijerph192013442
24. Habib, R. Z., Poulose, V., Alsaidi, R., al Kendi, R., Iftikhar, S. H., Mourad, A.-H. I., Kittaneh, W. F., & Thiemann, T. (2022). Plastic cutting boards as a source of microplastics in meat. Food Additives & Contaminants: Part A, 39(3), 609–619. https://doi.org/10.1080/19440049.2021.2017002
25. Schymanski, D., Humpf, H.-U., & Fürst, P. (2020). Determination of particle abrasion through milling with five different salt grinders – a preliminary study by micro-Raman spectroscopy with efforts towards improved quality control of the analytical methods. Food Additives & Contaminants: Part A, 37(8), 1238–1252. https://doi.org/10.1080/19440049.2020.1748724

26. Kim, S., Jo, E. H., & Choi, S. (2022). Microplastic release from damaged commercial teabags. Membrane and Water Treatment, 13(1), 21–28. https://doi.org/10.12989/MWT.2022.13.1.021

27. Banaei, G., Abass, D., Tavakolpournegari, A., Martín-Pérez, J., Gutiérrez, J., Peng, G., Reemtsma, T., Marcos, R., Hernández, A., & García-Rodríguez, A. (2024). Teabag-derived micro/nanoplastics (true-to-life MNPLs) as a surrogate for real-life exposure scenarios. Chemosphere, 368, 143736. https://doi.org/10.1016/j.chemosphere.2024.143736

28. Banaei, G., García-Rodríguez, A., Tavakolpournegari, A., Martín-Pérez, J., Villacorta, A., Marcos, R., & Hernández, A. (2023). The release of polylactic acid nanoplastics (PLA-NPLs) from commercial teabags. Obtention, characterization, and hazard effects of true-to-life PLA-NPLs. Journal of Hazardous Materials, 458, 131899. https://doi.org/10.1016/j.jhazmat.2023.131899

29. Busse, K., Ebner, I., Humpf, H.-U., Ivleva, N., Kaeppler, A., Oßmann, B. E., & Schymanski, D. (2020). Comment on "Plastic Teabags Release Billions of Microparticles and Nanoparticles into Tea." Environmental Science & Technology, 54(21), 14134–14135. https://doi.org/10.1021/acs.est.0c03182

30. BfR (German Federal Institute for Risk Assessment). (2025). BfR assesses study on tea bags and microplastic particles: No health impairments expected based on current knowledge. Communication 029/2025. Available at https://www.bfr.bund.de/en/notification/bfr-assesses-study-on-tea-bags-and-microplastic-particles/ (Accessed: 5 Oct 2025).

31. Hernandez, L. M., Xu, E. G., Larsson, H. C. E., Tahara, R., Maisuria, V. B., & Tufenkji, N. (2019). Plastic Teabags Release Billions of Microparticles and Nanoparticles into Tea. Environmental Science & Technology, 53(21), 12300–12310. https://doi.org/10.1021/acs.est.9b02540

32. Oßmann, B. E., Sarau, G., Holtmannspötter, H., Pischetsrieder, M., Christiansen, S. H., & Dicke, W. (2018). Small-sized microplastics and pigmented particles in bottled mineral water. Water Research, 141, 307–316. https://doi.org/10.1016/j.watres.2018.05.027

33. Zangmeister, C. D., Radney, J. G., Benkstein, K. D., & Kalanyan, B. (2022). Common Single-Use Consumer Plastic Products Release Trillions of Sub-100 nm Nanoparticles per Liter into Water during Normal Use. Environmental Science & Technology, 56(9), 5448–5455. https://doi.org/10.1021/acs.est.1c06768

34. Duda, A., & Petka, K. (2025). The Presence of Micro- and Nanoplastics in Food and the Estimation of the Amount Consumed Depending on Dietary Patterns. Molecules, 30(18), 3666. https://doi.org/10.3390/molecules30183666

35. He, Y.-J., Qin, Y., Zhang, T.-L., Zhu, Y.-Y., Wang, Z.-J., Zhou, Z.-S., Xie, T.-Z., & Luo, X.-D. (2021). Migration of (non-) intentionally added substances and microplastics from microwavable plastic food containers. Journal of Hazardous Materials, 417, 126074. https://doi.org/10.1016/j.jhazmat.2021.126074

36. Hossain, M. B., Yu, J., Banik, P., Noman, Md. A., Nur, A.-A. U., Haque, Md. R., Rahman, Md. M., Albeshr, M. F., & Arai, T. (2023). First evidence of microplastics and their characterization in bottled drinking water from a developing country. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1232931

37. Yang, C., Xie, J., Gowen, A., & Xu, J.-L. (2024). Machine learning driven methodology for enhanced nylon microplastic detection and characterization. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-54003-1

38. Yousefi, A., Attar, H. M., & Yousefi, Z. (2024). Investigating the release of microplastics from tea bags into tea drinks and human exposure assessment. Environmental Health Engineering and Management, 11(3), 337–347. https://doi.org/10.34172/ehem.2024.33

39. Mikac, L., Csáki, A., Zentai, B., Tolić, A., Ivanda, M., & Veres, M. (2024). Effects of Gamma Irradiation on Polyethylene Terephthalate and Detection of Microplastic Particles Down to 1 µm. Langmuir, 40(21), 10916–10924. https://doi.org/10.1021/acs.langmuir.4c00252

40. Hagelskjær, O., Hagelskjær, F., Margenat, H., Yakovenko, N., Sonke, J. E., & Le Roux, G. (2025). Majority of potable water microplastics are smaller than the 20 µm EU methodology limit for consumable water quality. PLOS Water, 4(1), e0000250. https://doi.org/10.1371/journal.pwat.0000250

41. Yadav, H., Khan, M. R. H., Quadir, M., Rusch, K. A., Mondal, P. P., Orr, M., Xu, E. G., & Iskander, S. M. (2023). Cutting Boards: An Overlooked Source of Microplastics in Human Food? Environmental Science & Technology, 57(22), 8225–8235. https://doi.org/10.1021/acs.est.3c00924
42. Winkler, A., Santo, N., Tremolada, P., Parolini, M., Pasini, V., Ortenzi, M. A., & Bacchetta, R. (2020). Microplastic Release from Plastic Bottles - Comparison of Two Analytical Methodologies (SEM-EDX and μ-FTIR). In Springer Water (pp. 255–261). Springer International Publishing. https://doi.org/10.1007/978-3-030-45909-3_40
43. European Food Safety Authority (EFSA), Barthélémy, E., Cariou, R., Castle, L., Crebelli, R., Di Consiglio, E., Dumas, T. H., Franz, R., Grob, K., Lambré, C., Lampi, E., Milana, M. R., Pronk, I. M. G. M., Rivière, G., da Silva, M., Tietz, T., Tsochatzis, E., & Van Hoeck, E. (2025). Literature review on micro- and nanoplastic release from food contact materials during their use [JB]. EFSA Supporting Publications, 22(10). https://doi.org/10.2903/sp.efsa.2025.EN-9733
44. Przygoda-Kuś, P., Kosiorowska, K. E., Urbanek, A. K., & Mirończuk, A. M. (2025). Current Approaches to Microplastics Detection and Plastic Biodegradation. Molecules, 30(11), 2462. https://doi.org/10.3390/molecules30112462
45. Vogel, A., Tentschert, J., Pieters, R., Bennet, F., Dirven, H., van den Berg, A., Lenssen, E., Rietdijk, M., Broßell, D., & Haase, A. (2024). Towards a risk assessment framework for micro- and nanoplastic particles for human health. Particle and Fibre Toxicology, 21(1). https://doi.org/10.1186/s12989-024-00602-9
46. Wang, J., Lee, J., Kwon, E. E., & Jeong, S. (2023). Quantitative analysis of polystyrene microplastic and styrene monomer released from plastic food containers. Heliyon, 9(5), e15787. https://doi.org/10.1016/j.heliyon.2023.e15787
47. Wang, L., Gao, J., Wu, W.-M., Luo, J., Bank, M. S., Koelmans, A. A., Boland, J. J., & Hou, D. (2024). Rapid Generation of Microplastics and Plastic-Derived Dissolved Organic Matter from Food Packaging Films under Simulated Aging Conditions. Environmental Science & Technology, 58(45), 20147–20159. https://doi.org/10.1021/acs.est.4c05504
48. Wang, Y., Wang, Z., Lu, X., Zhang, H., & Jia, Z. (2023). Simulation and Characterization of Nanoplastic Dissolution under Different Food Consumption Scenarios. Toxics, 11(7), 550. https://doi.org/10.3390/toxics11070550
49. Caponigro, V., Di Fiore, C., Carriera, F., Iannone, A., Malinconico, A., Campiglia, P., Crescenzi, C., & Avino, P. (2025). Evaluating microplastic emission from takeaway containers: A Micro-Raman approach across diverse exposure scenarios. Food Chemistry, 464, 141716. https://doi.org/10.1016/j.foodchem.2024.141716
50. Chen, H., Xu, L., Yu, K., Wei, F., & Zhang, M. (2023). Release of microplastics from disposable cups in daily use. Science of The Total Environment, 854, 158606. https://doi.org/10.1016/j.scitotenv.2022.158606
51. Chen, Y., Xu, H., Luo, Y., Ding, Y., Huang, J., Wu, H., Han, J., Du, L., Kang, A., Jia, M., Xiong, W., & Yang, Z. (2023). Plastic bottles for chilled carbonated beverages as a source of microplastics and nanoplastics. Water Research, 242, 120243. https://doi.org/10.1016/j.watres.2023.120243
52. Crosta, A., Parolini, M., & De Felice, B. (2023). Microplastics Contamination in Nonalcoholic Beverages from the Italian Market. International Journal of Environmental Research and Public Health, 20(5), 4122. https://doi.org/10.3390/ijerph20054122
53. Dessì, C., Okoffo, E. D., O'Brien, J. W., Gallen, M., Samanipour, S., Kaserzon, S., Rauert, C., Wang, X., & Thomas, K. V. (2021). Plastics contamination of store-bought rice. Journal of Hazardous Materials, 416, 125778. https://doi.org/10.1016/j.jhazmat.2021.125778
54. Ranjan, V. P., Joseph, A., & Goel, S. (2021). Microplastics and other harmful substances released from disposable paper cups into hot water. Journal of Hazardous Materials, 404, 124118. https://doi.org/10.1016/j.jhazmat.2020.124118
55. Vega-Herrera, A., Garcia-Torné, M., Borrell-Diaz, X., Abad, E., Llorca, M., Villanueva, C. M., & Farré, M. (2023). Exposure to micro(nano)plastics polymers in water stored in single-use plastic bottles. Chemosphere, 343, 140106. https://doi.org/10.1016/j.chemosphere.2023.140106

56. Qian, N., Gao, X., Lang, X., Deng, H., Bratu, T. M., Chen, Q., Stapleton, P., Yan, B., & Min, W. (2024). Rapid single-particle chemical imaging of nanoplastics by SRS microscopy. Proceedings of the National Academy of Sciences, 121(3). https://doi.org/10.1073/pnas.2300582121
57. Yang, W., Li, Y., Wang, X., Zheng, Y., Li, D., Zhao, X., Yang, X., & Shan, J. (2024). One-stop quantification of microplastics and nanoparticles based on meniscus self-assembly technology. Science of The Total Environment, 949, 174946. https://doi.org/10.1016/j.scitotenv.2024.174946

Funds:
This work was supported by the Slovak Research and Development Agency, grant No. APVV-23-0036.

Acknowledgments:
-

Competing Interests:
No potential conflict of interest was reported by the author(s).

Ethical Statement:
This article does not contain any studies that would require an ethical statement.

AI Statement:
This article was written by the authors, with AI tools used solely for grammar and language correction.

Contact Address:

Jozef Čapla
Affiliation: The Slovak University of Agriculture in Nitra, Faculty of Biotechnology and Food Sciences, Department of Food Science, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia,
Tel.: +421 37 641 4371
E-mail: jozef.capla@uniag.sk
ORCID: https://orcid.org/0000-0001-9475-6359
Author contribution: conceptualisation, methodology, writing – original draft, writing – review & editing, funding acquisition.

Peter Zajác
Affiliation: The Slovak University of Agriculture in Nitra, Faculty of Biotechnology and Food Sciences, Department of Food Science, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia,
Tel.: +421 37 641 4371
E-mail: peter.zajac@uniag.sk
ORCID: https://orcid.org/0000-0001-9475-6359
Author contribution: conceptualisation, writing – original draft, writing – review & editing.

Jozef Čurlej
Affiliation: The Slovak University of Agriculture in Nitra, Faculty of Biotechnology and Food Sciences, Department of Food Science, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia,
Tel.: +421 37 641 5825
E-mail: jozef.curlej@uniag.sk
ORCID: https://orcid.org/0000-0003-0039-5332
Author contribution: conceptualisation, writing – original draft, writing – review & editing.

Martina Fiksleová
Affiliation: The Slovak University of Agriculture in Nitra, Faculty of Biotechnology and Food Sciences, Department of Food Science, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia,
Tel.: +421 37 641 5825
E-mail: martina.fikselova@uniag.sk
ORCID: https://orcid.org/0000-0002-0962-3437
Author contribution: conceptualisation, writing – original draft, writing.

Simona Kunová
Affiliation: The Slovak University of Agriculture in Nitra, Faculty of Biotechnology and Food Sciences, Department of Food Science, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia,
Tel.: +421 37 641 5825
E-mail: simona.kunova@uniag.sk
ORCID: https://orcid.org/0000-0003-2240-1756
Author contribution: conceptualisation, writing – original draft, writing.

Corresponding author: **Peter Zajác**