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REVIEW

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Nanoplastic Contamination in Commercially Available Carbonated Beverages and Its Potential Human Health Consequences

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Abstract

Nanoplastics defined as plastic particles with diameters less than 100 nanometers, have become a growing concern due to their widespread presence in consumable goods. The small size and unique chemical properties of nanoplastics make them highly mobile & potentially hazardous to human health. Nanoplastic can enter the human body through the respiratory system via inhalation and, the digestive tract via consumption of contaminated food and water, which compromise immune defenses and increase susceptibility to infections. It influences microbial community dynamics by altering the balance between commensal and pathogenic species. Bioaccumulation of plastics in the human body can potentially lead to infectious diseases, including respiratory disorders like lung cancer and asthma. It can induce apoptosis in cells and have genotoxic and cytotoxic effects. The role of nanoplastics in altering ecological microbial communities and their potential to introduce novel pathogens highlight their contribution to the emergence of infectious diseases. These dynamics are critical for mitigating the risks posed by nanoplastics and require interdisciplinary research in the future.

Keywords: Nanoplastics; Microbial community; Bioaccumulation; Gut microbiota; Apoptosis

Introduction

The last ten years have seen a significant increase in awareness of plastic pollution in the environment as plastic breaks down to generate microplastics ranging from 1 micrometer to 5 micrometers and nanoplastics lesser than 1 micrometer (Pradel et al., 2023). Demonstrated how common single-use food-grade plastics, including polyethylene terephthalate (PET), can emit significant amounts of nanoplastics when heated or stored over a long time (Zhang et al., 2024). Data indicate that quantities of nanoplastic in bottled beverages, including fruit juices, might rise to 10^{-9} particles/ml, especially when kept in environments that encourage the breakdown of plastics (Cavazzoli et al., 2023). The environmental breakdown of plastics and the subsequent production of nanoplastics may eventually end up in food items (Hadri et al., 2020). Several environmental and health issues have also been brought on by the extensive use of plastics. Plastic is widely utilized for a number of reasons in the food and beverage sector, such as processing, storage, transportation, and packaging (Ma et al., 2024). (PE-LD/PE LLD) are examples of nanoplastics found in food and beverages (Sahail et al., 2023). In packaging, PET (Polyethylene terephthalate) is being utilized more because of its great physical features, transparency, resistance to UV light, and strong oxygen barrier capabilities, among the things for which PET has been suggested as a packaging material (Chumillas et al., 2007). Nanoplastic is an "invisible threat", emphasizing their ubiquity in the environment and potential to accumulate in food chains (Joksimovic et al., 2022). The environmental routes by which nanoplastic get into the food chain must also be taken into account.

The presence of nanoplastic in juice may be due to environmental contamination as well as packing, biological processes can break down microplastic into nanoplastic (Dawson et al., 2018). It's conceivable that nanoplastics come from sources beyond the food itself, such as manufacturing aids, water utilized, air, or equipment or machinery. It's also feasible that the level of nanoplastic grows throughout processing (Alexander et al., 2016). The health complications of nanoplastic consumption through beverages and food are still being elucidated and the potential health impacts within the human food production chain, suggesting that these particles could lead to toxicological effects similar to those observed with engineered nanoparticles. Inhalation refers to occupational exposure that includes aerosols containing nanoplastic, possible contact through personal care items, and ingestion of nanoplastic particles through beverage consumption (Lehner et al., 2019). The ingestion of these particles could lead to various health issues, including disruption and inflammation of gut microbiota (Paul et al., 2020). Due to their innate tendency to cause intestinal blockage or tissue abrasion, nanoplastic particles may physically harm intestinal mucosa, they may also be poisonous when present in their physical form (Molina et al., 2022). Detecting techniques in food samples are TEM, SEM and PyrGc-Ms (Adhikari et al., 2021).

Resources and transport of nanoplastics in juices

Packaging

The beverage sector makes extensive use of paper cups, plastic containers, glass bottles, cans and reusable plastic bottles due to their variety, portability, and extended storage duration, large volumes of plastic debris may dissolve into beverages as a result of these features, though (Ma et al., 2024). Plasticizers to render the material flexibility, stability, thermal stabilizers, colorings, and flame retardants, for example in HDPE (High Density Polyethylene) and PET (Polyethylene Terephthalate) to the level plastic product additives, such as Bisphenol A, phthalates, have a negative impact on health of human or animal populations is a topic of intense debate (Rastkari et al., 2018). Human exposure to bisphenol A primarily occurs through nutrition, including packaged beverages and meals that have been contaminated by BPA leaking from packaging and there is currently insufficient information available regarding the amounts of BPA in fruit juice (Khan et al., 2021). Concerns regarding the exposure of consumers to hazardous substances are raised by the fact that the presence of acidic components in juices can facilitate the migration of these compounds from the container into the liquid (Rastkari et al., 2018; Carneado, 2023). According to a study, PET nanoplastic is less hydrophobic than other materials, which makes it easier for them to pass through cell membranes and possibly into food products, the type of polymer has a significant impact on the migratory dynamics of nanoplastic, additionally the aging of plastic materials can alter their surface properties further influencing the extent of nanoplastic migration (Li et al., 2023). Higher rates of leaching into beverages kept in PET bottles, especially when stored for an extended period of time or at high temperatures (Wang et al., 2023).

Processing

Juice packaging and storage in plastic containers may cause nanoplastic to seep out of packaging, research shows that when exposed to high temperatures or extended contact with acidic liquids like fruit juices, typical food-grade plastics like PET, LDPE can produce a large amount of nanoplastic (Zhang et al., 2023). In food goods that are packaged, with the suspicion that they might also have routes through various industrial processes and during packing. Given that they are made using various formulas and manufacturing techniques for direct consumption and that water is their primary ingredient, packaged beverages in particular have drawn a lot of interest (Shruti et al., 2021). Juice bottle transportation can sometimes make the issue worse, impacts and vibrations that cause mechanical stress during transportation can cause plastic materials to break apart, which further contributes to the creation of nanoplastic (Ekvall et al., 2019). Apart from mechanical consideration, the chemical interaction between juice and the plastic packaging can help nanoplastic migrate, the acidic content of many fruit juices can rush the breakdown of plastic stuff, causing microscopic particles to be released (Habib et al.,2022). Certain additives or preservatives may increase the release of these pollutants from containers, and the chemical composition of juices might affect the amount of nanoplastic leaching (Cella et al., 2022). Nanoplastic and heavy metals released from carbonated beverages are influenced by carbon dioxide filling volume, storage sugar content, temperature, freeze-thaw and additions, the study evaluated the consequences of CO_2 bubbles and pressure separately and in combination on the release of nanoplastic brought on by CO_2 filling (Chen et al., 2023).

Occurrence and detection of nanoplastics in fruit juices

The physiochemical properties of nanoplastics have been accessed using a variety of methods, many of which are practical for identifying, measuring, and characterizing nanoplastic (Sohail et al.,2023). Numerous systematic analytical techniques have investigated various methods for particle identification and description (Cella et al., 2022). It has been found in a variety of food matrices, the need for sensitive detection techniques. The study highlights the need for scalable synthesis methods to produce efficient Surface-Enhanced Raman Spectroscopy (SERS) substrates, which can greatly increase the sensitivity of nanoplastic detection in intricate matrices such as juice. juice goods, considering that complex liquid matrices present comparable difficulties. The authors stress how crucial it is to attain low detection limits in order to guarantee food safety (Carreón, 2024). Among analytical methods, chemical characterization techniques such as spectroscopy-based and microscopic-based SEM, TEM, FTIR, Raman spectroscopy, (Pyr-Gc-Ms) (Mariano et al., 2021).

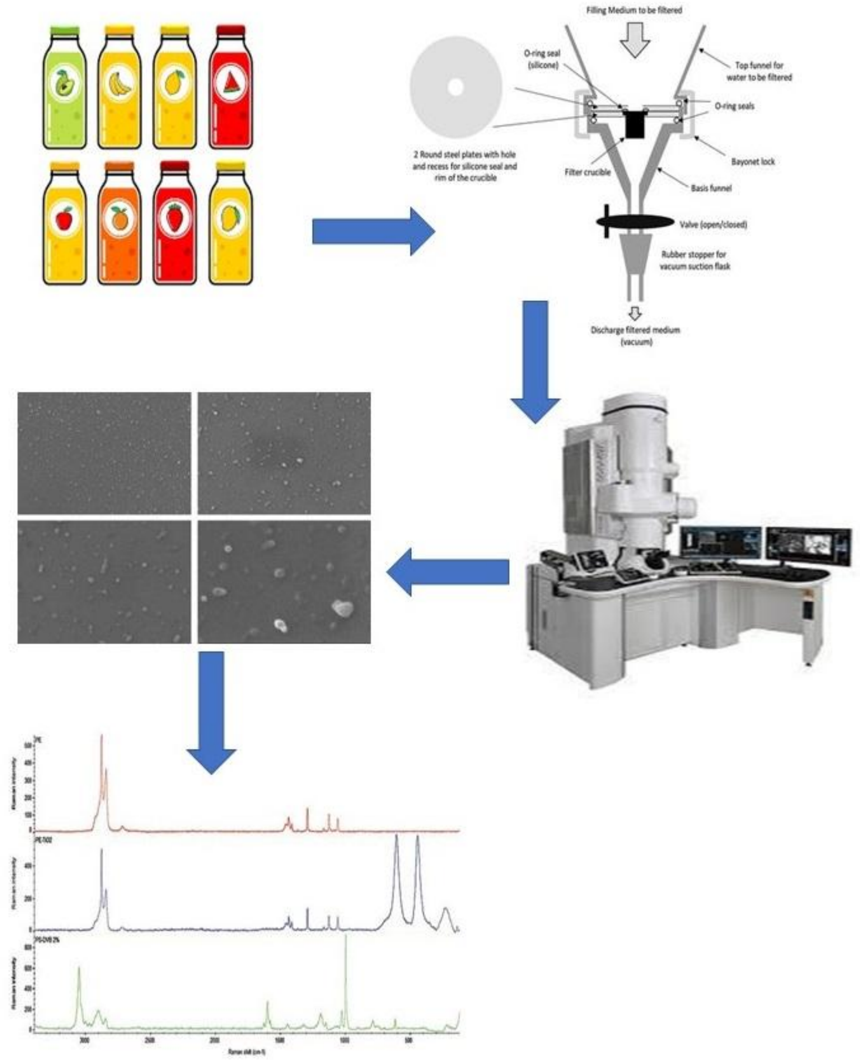

Fig. 1. Nanoplastic detection in fruit juices

Challenges and limitations in detecting nanoplastic in juices

It is difficult to quantify and identify nanoplastic because the majority of analytical tools used in research labs were not designed to analyze micro- and submicron-sized particles (Adhikari et al., 2021). NPs are still elusive, and it might be difficult to detect and quantify plastic debris in human biofluids and tissues, particularly in air samples and in human and animal tissues (Sendra et al., 2020). There is quantitative information on the prevalence and distribution of environmental microplastics, but there are no trustworthy methods for assessing nanoplastics in the environment because the existing detection techniques are so immature (Cai et al., 2021). With the wide range of characteristics including size, shape, density, polymer type, and surface properties and the complexity and diversity of, sources, consumption trends, exposure routes, and material characteristics of plastic sophisticated techniques are needed for accurate characterization, measurement, and determination possibly a most difficult tasks in the environment and food (Ivleva, 2021). Sample preparation involves washing, filtering, and centrifuging in order to separate micro and nanoplastic from complex environmental, food, and beverage materials. The new characteristics of plastic pollution make sample preparation and analysis much more difficult, and there is regrettably no established standard or technique for sample preparation, especially for nanoplastic (Fang et al., 2023). A small number of analytical techniques are appropriate for nanoplastic, although they are frequently used for nanoplastics. These techniques are used in different methods, mass spectrometry, molecular spectroscopy, elemental analysis, microscopy, and specialized microscopes like TEM and SEM. However, they are unable to identify a particular plastic because of insufficient chemical information (You et al., 2024). Data on possible exposure of marine species to nanoplastic is severely lacking, it restricts risk evaluation because it is currently difficult to observe and quantify tiny particles mostly because of existing methodological limitations. Environmental data on nanoplastic exposure is scarce, and laboratory tests are problematic since many research lack appropriate experimental controls, quality criteria, appropriate data or results, or risk assessment (Catarino et al., 2023).

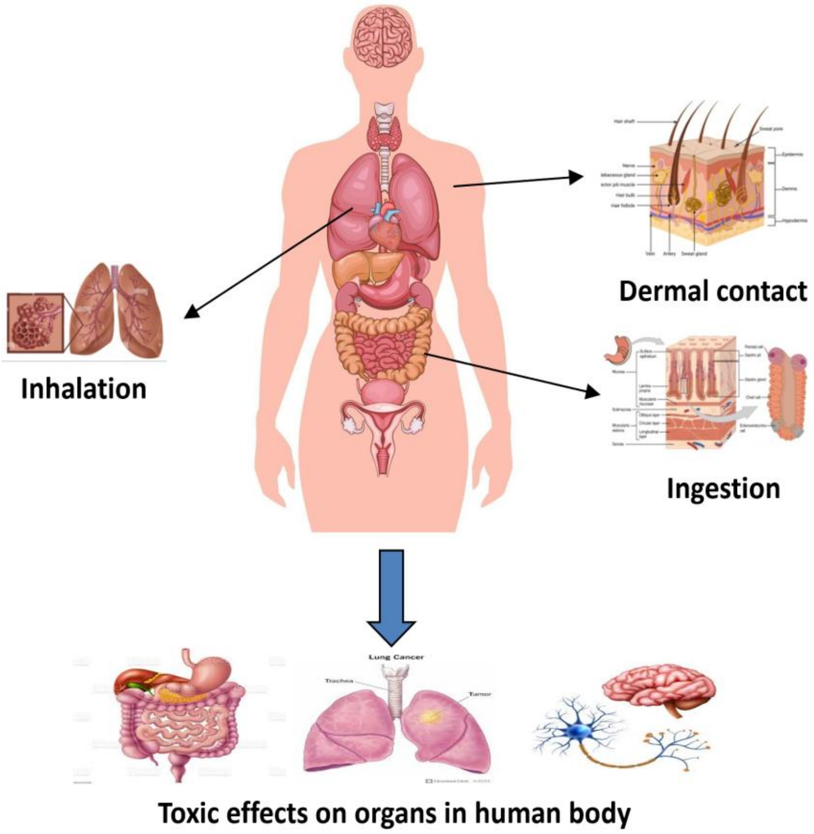

Fig. 2. Human health consequences of nanoplastics

Potential human health consequences

Several factors the inherent nature of polymers, the leaching effects of plastic additives and the potential adherence of contaminants have raised concerns about nanoplastic as possible toxicants (Rubio et al., 2020). The food chain transfer method can also pass nanoplastic from low trophic level species to high nutrition organisms or even the human body by ingestion or attachment (Zhang et al., 2022). The bioaccumulation of plastics in the human body may result in infectious diseases, including respiratory conditions like pulmonary cancer and pneumonia.

Table 1. Type of nanoplastics and their health consequences

S. No.	Type of nanoplastics	Human health consequences	Reference
1	BPA	Several endocrine disorders PCOS, and other metabolic problems, hormone-dependent tumors such as breast and prostate cancer, infertility, and premature puberty	Ugoeze et al. (2021)
2.	Polystyrene	Impact on the lungs, liver, kidney, reproductive organs, defenses, digestion, neurobehavioral consequences and DNA damage.	Gouin et al. (2024)
3.	polyethylene	Cell membrane disruption Nanoplastic can integrate into lipid bilayers, potentially disrupting cell membrane integrity and function	Gehrke et al. (2020)
4	Polypropylene	Absorbed by intestinal cells, raising concerns about their impact on gut health and systemic distribution	Sun (2024)

Plastics can enter the body through the respiratory system by respiration and through the GI tract and affect gut microbiota. It can induce cytotoxic and genotoxic effects and cause cell death (Winiarska et al., 2024). Metabolic and cardiovascular illnesses like diabetes, obesity, and atherosclerosis may be caused by exposure to NPs, which have been shown to induce inflammation, oxidative stress, and changes in glycolipid metabolism (Zheng et al., 2024). Numerous studies have confirmed the impact of nanoplastics on infertility, cancer, inflammation, gastrointestinal disorders, and other conditions. Components including PC, PET, and PE have been found in a number of human samples. Uncertainty surrounds the physiologic effects of both acute and long-term nanoplastic intake on human systems (Rai, 2022). The infiltration of micro/nanoplastic crosses the intestinal membrane, which further changes the population of GI Tract microbes and triggers by turning on particular gut barrier receptors, the inflammatory mediators. Additionally, when NPs alter microbial diversity, the blood-brain barrier breaks down and metabolites (such as SCFAs and LPS) are translocated through the vagus nerve (Ghosh et al., 2024). Consumed NPs have been shown to have a propensity to cross the intestinal barrier and accumulate in the body, as well as to impact a variety of human cell functions, including Madin-Darby canine kidney (MDCK) The reproductive toxic effects of NPs in mammals are also being investigated more and more (Xu et al., 2022). The main ways that NPs are exposed are through ingestion, inhalation, and skin contact. Other oxidative stress, cytotoxicity, DNA damage, inflammation, immunological response, neurotoxicity, metabolic disturbance, and eventually detrimental effects on the nervous, respiratory, reproductive and digestive systems (Sangkham et al., 2022).

Conclusion

Mitigation strategies for nanoplastic contamination in food systems must include robust regulatory frameworks and systemic approaches to address sustainability challenges effectively. Establishing guidelines for acceptable levels of nanoplastics in food products is essential to ensure consumer safety, alongside further research to understand long-term health and environmental impacts. While plastic remains a dominant material in food packaging due to its affordability, lightweight nature, and convenience, its harmful effects on the environment, including greenhouse gas emissions, necessitate a shift toward sustainable alternatives. Consumers frequently use plastic containers for food and beverage storage, highlighting the need for protective packaging that balances convenience with safety and sustainability. Public perception of risk plays a crucial role in shaping environmental and health policies, as awareness influences behavioral change at both individual and societal levels. However, simply providing information is often insufficient in driving meaningful change. Encouraging responsible plastic use requires interdisciplinary efforts that integrate scientific research, policy interventions, and consumer engagement. By fostering sustainable practices and promoting alternatives, society can reduce plastic pollution and contribute to a healthier environment. Addressing the complexities of plastic-related issues demands collaborative action from governments, industries, and individuals to ensure long-term sustainability and public well-being.

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