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Review

Styrene migration from food contact materials

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ABSTRACT

Styrene is an organic compound widely used in the production of plastics for food packaging. The main aim of this review is to compile information on the risks associated with exposure to styrene, evaluating and comparing studies that address the methods for determining the styrene migration, the factors that affect such migration and the consequences of this substance on Human Health.

Current evidence indicates that styrene levels in food generally remain within regulatory limits; however, cumulative exposure from multiple sources, including food packaging and the environment, requires further investigation. Packaging materials and food processing methods can influence styrene migration, underscoring the need for context-specific assessment. Continuous monitoring and periodic updates to safety standards are essential to ensure long-term consumer protection. Moreover, transitioning towards a Circular Economy, through sustainable reuse and recycling of plastics, is critical for minimizing styrene release and achieving safer, more environmentally friendly food packaging solutions.

1. Introduction

Food Contact Materials (FCMs) refer to all materials and articles intended to come into contact with food and drink, such as containers, packaging, kitchen utensils, cutlery, and plates (Food contact materials, EFSA, 2024). They also include materials used in food processing equipment, such as coffee machines, food production machines and any kind of material in contact with food in any step of the process. FCMs can be made from a wide range of materials such as plastics, rubber, paper, ceramic, silicones, cork, and metal (Food contact materials, EFSA, 2024) as well as adhesives, varnishes and coatings and printing inks.

Continuous contact between food and FCMs can lead to the migration of certain substances, so called Food Contact Chemicals (FCCs), and consequent alteration of properties (appearance, flavor, and smell), compromising their quality and chemical safety, constituting a risk to consumer health (Silva et al., 2009; Muncke et al., 2017).

During the production of plastics, one of the most used materials in food packaging manufacture, intentionally added substances (IAS) as well as non-intentionally added substances (NIAS), may be present (Tsochatzis, 2021). IAS are the monomers and production chemicals (e.g. antioxidants, plasticisers), while NIAS can be impurities present in raw materials or substances generated through reaction and degradation

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Abbreviations: [Ca^{2+}]ER, Endoplasmic Reticulum Calcium; ABS, Acrylonitrile Butadiene Styrene; EB, Ethylbenzene; EBHP, Ethylbenzene Hydroperoxide; EFSA, European Food Safety Authority; EPS, Expanded Polystyrene; EU, European Union; FCCs, Food Contact Chemicals; FCMs, Food Contact Materials; FDA, Food and Drug Administration; FID, Flame Ionization Detector; GC, Gas Chromatography; GPPS, General Purpose Polystyrene; GSH, Glutathione (GSH); HDPE, High-Density Polyethylene; HIPS, High Impact Polystyrene; HPLC, High-Performance Liquid Chromatography; HS-SPME, Headspace Solid-Phase Microextraction; IAS, Intentionally Added Substances; MDA, Malondialdehyde (MDA); MMP, Mitochondrial Membrane Potential (MMP); MPs, Microplastics; MS, Mass Spectrometry; NIAS, Non-Intentionally Added Substances; NPs, Nanoplastics; OM, Overall Migration; OML, Overall Migration Limit; PET, Polyethylene Terephthalate; PS, Polystyrene; ROS, Reactive Oxygen Species; rPS, Recycled PS; SAN, Styrene-Acrylonitrile; SBC, Styrene-Butadiene Copolymer; SBR, Styrene-Butadiene Rubber; SM, Specific Migration; SML, Specific Migration Limit; SO, Styrene Oxide; STR, Styrene; TDI, Tolerable Daily Intake; WHO, World Health Organization; XPS, Extruded Polystyrene.

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processes (Oldring et al., 2023; Nerín et al., 2022). It is important to note that, although there is an extensive list of regulated substances and mixtures of IAS (> 1000) under Commission Regulation (EU) No. 10/2011, only 60 % have available analytical standards and there is limited availability of mass spectral data in analytical databases or libraries (European Commission, 2011; Tsochatzis, 2021). In the case of NIAS, the information is even more restricted, often making quantitative analysis impossible, since composition of materials used for production of polymers and food packaging are not available (confidential to the manufactures) (Nerin et al., 2013; Pilevar et al., 2019; Tsochatzis, 2021).

Therefore, the presence of a considerable number of unidentified substances in FCM of virgin, processed or recycled plastic represents a risk to food safety (European Commission., 2011). For this reason, researchers around the world have expressed concerns about the safety of FCMs and their potential adverse effects on human health due to their extensive use (Muncke et al., 2023).

Styrene has been recently highlighted as substance of concern and consequently, polystyrene trays and articles have been banned in some countries or withdrawn from the market. This is the case of straws for beverages, originally made of styrene, which have been substituted by other materials, such as paper and board, in Europe and USA.

Styrene migration from polystyrene packaging is governed by diffusion through the polymer and partitioning at the polymer–food interface, and is strongly affected by food composition (Guazzotti et al., 2023). Due to its non-polar and hydrophobic nature, styrene shows higher affinity for lipids, leading to greater migration into fatty foods because lipids promote polymer swelling, increase free volume, and enhance diffusion and solubilisation of the monomer. In contrast, migration into aqueous foods is considerably lower because of the low solubility of styrene in polar media and limited polymer swelling, while acidic matrices may slightly increase migration indirectly by accelerating polymer surface degradation. Temperature, storage time, residual monomer content, and polymer morphology further modulate mass transfer kinetics (Guazzotti et al., 2023). These mechanisms are well supported by studies demonstrating higher styrene migration into non-polar and alcoholic simulants than into aqueous ones (Paraskevopoulou et al., 2012) and by recent real-food data showing that fat content is a dominant factor influencing styrene migration into dairy products (Guazzotti et al., 2023).

There are several publications dealing with the potential damage caused by styrene, while others admit that there are not enough evidences for such toxicity. For this reason, it is important to review all published data and discussed the pros and cons of the presence of styrene in our lives. In this context, this review aims to summarize information about the potential risks associated with exposure to styrene, through the analysis and comparison of several studies that report the contamination process and the methods of detection and quantification of this compound. Conclusions are subsequently drawn, particularly regarding compliance with the limits legally imposed by the responsible regulatory authorities. Furthermore, and given the current climate changes and environmental concerns faced, different forms of recycling and possible innovations in terms of minimizing the release of this compound into the environment are also addressed, mentioning the importance of implementing a Circular Economy.

2. Styrene

Styrene (CAS No. 100-42-5), also known as ethenylbenzene, phenylethylene, vinylbenzene, cinnamene, or styrene monomer, is a clear, colorless liquid that evaporates easily and typically has a sweet odor. However, it often contains impurities that contribute to a sharp, unpleasant smell. Table S1 summarizes the main physicochemical properties of styrene (Styrene | Toxic Substances | Toxic Substance Portal | ATSDR, 2021).

Styrene (STR) was first discovered in 1831 as a distillation product of storax balsam, an exudate found in the sapwood and bark of *Liquidambar orientalis* and L. *styraciflua* trees (Miller et al., 1994). Actually, it is produced commercially from by-products of petroleum and natural gas and is an essential component of a wide range of robust, flexible, and lightweight products across various sectors (Miller et al., 1994). Styrene has been also identified as a metabolite released by *A. flavus* feeded with cinnamon (Becerril et al., 2019).

Styrene is produced mainly by catalytic dehydrogenation of ethylbenzene (EB), a chemical process in which ethylbenzene loses hydrogen to convert into styrene in the presence of catalysts (Fig. 1A). Typical catalysts are based on ferric oxide with the additives chromia and potassium oxide (Saunders, 1973). Styrene monomer is produced with high purity usually in the range of 99.7–99.9 %. The main impurity in the styrene is residual EB (Polystyrene for Food Packaging Applications ILSI Europe Report Series, 2017).

An alternative production route involves the co-generation of propylene oxide. In this process, ethylbenzene is first oxidized to ethylbenzene hydroperoxide (EBHP), which subsequently reacts with propylene to produce propylene oxide and α-methylphenylcarbinol. The latter is then dehydrated at 200 °C in the presence of alumina to yield styrene (Miller et al., 1994).

Styrene also occurs naturally in the environment and exists in small concentrations in various commonly consumed foods and beverages, such as coffee, strawberries, cinnamon, nuts, and meat (Styrene | Toxic Substances | Toxic Substance Portal | ATSDR, 2021; Styrene Exposure - SIRC, 2024).

Some essential items such as food containers, protective packaging, computer housings, consumer electronics, medical devices, automotive components, wind turbine parts, construction materials, and applications in defense and sports equipment contain polystyrene (PS), made from styrene monomer linked together in a long chain. PS is produced by a polymerization process using a thermal or catalyzed reaction of styrene monomer (Fig. 1B) (Tosello & Hansen, 2006).

Typically, for thermoplastics like polystyrene, the value of *n* (Fig. 1B) is between approximately 10^3 to 10^5 monomer units to form solids with useful mechanical properties (Martin, 2006). This range reflects the degree of polymerization, where lower values indicate shorter chains with fewer repeating units, and higher values indicate longer chains with many repeating units. The specific value of *n* influences the properties of the polystyrene, such as its molecular weight, mechanical strength, and processing characteristics(Speight, 2020).

Styrene serves as a key building block for a wide range of materials, each with distinct properties and applications. These include high-impact polystyrene (HIPS), styrene–butadiene copolymer (SBC), general-purpose polystyrene (GPPS), acrylonitrile–butadiene–styrene

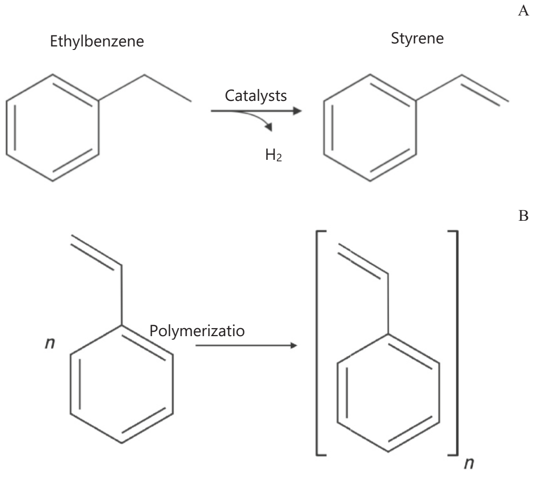

Fig. 1. A. Synthesis of styrene by catalytic dehydrogenation of high-purity ethylbenzene; B. Polystyrene polymerization.

(ABS), styrene–acrylonitrile (SAN), expanded polystyrene (EPS), extruded polystyrene (XPS), and styrene–butadiene rubber (SBR). These materials are widely used in food packaging, disposable products, industrial components, and thermal insulation (Chung et al., 2013). In 2025, the European Food Safety Authority (EFSA) reassessed the safety of styrene in food contact materials and concluded that styrene is not genotoxic following oral exposure and can be considered safe when migration levels remain below the Specific Migration Limit (SML) of 40 parts per billion (ppb) (EFSA's Re-Assessment of Styrene Safety for Use in Plastic Food Contact Materials, 2025).

Styrene-based plastics rank among the most versatile, easily processed, and cost-effective polymer materials (Table S2). One of the most common food packaging materials is polystyrene (PS) (Brandsch & Schuster, 2020; Sadighara, Abedini, et al., 2022). PS is a thermoplastic that softens upon heating and can be transformed into a wide variety of products via semi-finished forms such as films and sheets. Its amorphous structure makes it particularly suitable for several processing techniques, including injection molding, sheet extrusion, and thermoforming (Polystyrene for Food Packaging Applications ILSI Europe Report Series, 2017; Yam, 2009). A commonly used variation is High Impact Polystyrene (HIPS), which is modified with polybutadiene rubber to improve impact resistance. HIPS is widely used in food contact applications such as yogurt pots, disposable cutlery, glass-like cups, trays, and bottles, due to its enhanced toughness and ease of processing. However, polystyrene is generally prone to stress cracking when exposed to organic liquids and oils, which restricts its application for packaging foods with high fat or vegetable oil content (Polystyrene for Food Packaging Applications ILSI Europe Report Series, 2017).

EPS has been used for food trays in the market over years. Although the postconsumer material can be recycled, the lack of selective collection and recycling process drove the ban of EPS as food trays in several countries.

But as happens with all plastics, some additives are needed to provide the required functionality to the polymer and some oligomers remain also in the final polymer. All these molecules are usually of small size, lower than 1000 Da, and can be transferred to the food in contact with the polymer. Sub-sections below will deep with these issues.

2.1. Exposure

Styrene exposure mainly occurs in workplaces involved in the manufacture of styrene or in the production of essential industrial, consumer and medical polymers and copolymers, including PS, SBR, unsaturated polyester resins, SBL, ABS, and SAN (Styrene Exposure - SIRC, 2024).

The general public can be exposed to styrene through sources such as industrial emissions, engine exhaust fumes, tobacco smoke, household furnishings and building materials (Styrene Exposure - SIRC, 2024). Even so, exposure levels are considered low in ambient air, with higher concentrations indoors, mainly in homes (Werder et al., 2019).

Exposure to styrene can occur in two main ways. (1) direct migration from the packaging: styrene can migrate from food packaging materials into the food and beverages although the concentration level is usually very low (Nerín et al., 1998; Salafranca et al., 2000; Song et al., 2019). This migration can occur when styrene-based materials release small amounts of styrene into the food or drink they hold; (2) natural presence in foods: some foods naturally contain styrene or its precursors. For example, cinnamon has higher levels of natural styrene due to the oxidation of cinnamaldehyde, its main flavoring compound. In cinnamon, styrene concentrations can reach up to 40 ppm (ppm), which is considerably higher than in most other foods (Styrene Exposure - SIRC, 2024). Styrene is not generally found at measurable levels in drinking water for the general population, although local contamination can occur (Styrene Exposure - SIRC, 2024).

A comprehensive assessment of styrene exposure requires integrating contributions from all major sources, including migration from food packaging, environmental contamination, and occupational settings, because humans are simultaneously exposed through multiple pathways. Accurate estimation of overall health risk therefore needs a cumulative exposure framework that quantifies doses from each source and expresses them on a comparable internal dose basis. Physiologically based pharmacokinetic (PBPK) models are essential for this purpose, as they account for styrene's route-specific absorption and rapid metabolism to styrene-7,8-oxide, its primary toxic metabolite (Bus et al., 2024). Risk characterization should consider both cancer and non-cancer endpoints, given styrene's classification as "probably carcinogenic to humans" (Group 2 A) by the International Agency for Research on Cancer (IARC, 2018). Ultimately, the accuracy of cumulative risk estimation depends on harmonizing data from food-contact migration studies, environmental monitoring, occupational exposure assessments, and human biomonitoring to derive an integrated metric reflecting realistic combined exposures.

The comprehensive exposure models that integrate laboratory migration data, dietary intake estimates, and human biomonitoring results provide a more accurate and holistic assessment of real-world styrene exposure.

2.2. Absorption, distribution, metabolism and excretion

A recent study by Leonard et al. (2024) reported polystyrene (PS) as one of the most commonly detected plastic polymers in human blood, using the μFTIR technique. However, probably the findings are not PS but styrene monomer or oligomers, as the μFTIR technique can detect not only plastic polymers but also their monomers or oligomers, which provide the same μFTIR response and are smaller chemical components derived from PS. (Leonard et al., 2024). It is also true that PS is the only commercial plastic as nanomaterial and microplastics and for this reason, many publications dealing with nanoplastics and microplastics studied the performance of PS.

In humans, styrene can be absorbed through all exposure routes, but inhalation is the primary pathway. Styrene vapors are readily absorbed through the lungs when contaminated air is inhaled (Werder et al., 2019). Percutaneous absorption of styrene is minimal when exposed to air concentrations up to 2.5 g/m^3 (600 ppm), accounting for only about 2 % compared to pulmonary absorption. However, when styrene comes into direct contact with the skin, percutaneous absorption rates are 9–15 mg/cm^2/h for liquid styrene and 40–180 μg/cm^2/h for aqueous solutions (66–269 mg/L) (Hazardous Substances Data Bank (HSDB): 171 - PubChem, 2024). These data indicate that while styrene can enter the body through various routes, PS, being a non-volatile solid polymer, is unlikely to be absorbed through inhalation of vapor or via the skin. Therefore, any PS found in the human body likely entered through alternative exposure routes, such as ingestion of microplastic particles or more probably ingestion of oligomers.

Following oral administration of styrene at a dose of 20 mg/kg, the compound predominantly accumulates in the kidneys, followed by the liver and pancreas. Styrene is soluble in blood and has been detected in fat tissue (Plotnick & Weigel, 1979). Styrene is primarily excreted through the renal pathway, with 90 % of the dose being eliminated in the urine within the first 24 h, while less than 2 % is recovered in the feces (Plotnick & Weigel, 1979).

Recent studies on the biodistribution of PS nanoplastics (NPs, size <100 nm) and microplastics (MPs, size ranging between 1 μm and 5 mm) in BALB/c mice reveal that NPs penetrate tissues more effectively, leading to more significant changes in liver, kidney, and heart functions. Consequently, a reduction in particle size and an increase in the administered dose result in a higher degree of toxicity (Table 1) (Du et al., 2024; Sarma et al., 2022). PS nanoparticles are commercially available and thus used for all studies concerning the influence of nanoparticles.

The first step in styrene metabolism is its enzymatic oxidation to styrene oxide (SO), primarily in the liver (Fig. 2). SO is a highly reactive

Table 1
Styrene absorption, distribution, metabolism, excretion: insights from Clinical Trials.

Authors/ Year	Study	Methods	Results	Conclusion
Du et al., 2024	Biodistribution of PS-MPs/NPs (50 nm, 100 nm, and 500 nm) in BALB/c mice. Administration: 1 mg/kg or 10 mg/kg of PS50, PS100, and PS500. Gavage, 100 μl per day for 28 consecutive days.	– Cryosection fluorescence microscopy (to observe PS accumulation and distribution in tissues) – Fluorescent microplate reader (quantification) – Histopathological, hematology and serum biochemical analysis	– Accumulation mainly in the liver, spleen, and intestine. – No abnormal behavior, weight changes and severe histopathological abnormalities. – Changes in hematological and biochemical parameters depending on particle size and dose.	NPs showed greater tissue penetration and induced more significant changes in liver, kidney, and heart functions.Toxicity increased with smaller particle size and higher dose.
Wang et al., 2024	Biodistribution of europium- or fluorescence-tagged PS-NPs in live chicken embryos at stages 18–19, following injection into the vitelline vein.	– Inductively coupled plasma mass spectrometry on tissue lysates – Paraffin histology	– High levels of PS-NPs in the heart, liver, and kidneys. – PS-NPs crossed the endocardium of the heart and the liver endothelium. – PS-NPs were detected in allantoic fluid, indicating excretion by the kidneys.	The chicken embryo model enhances understanding of the tissue-specific accumulation and biodistribution of PS-NPs in developing animals.
Jasinski et al., 2023	Distribution and excretion of submicrometer (0.2 and 0.5 μm) and micron-sized (3 μm) PS particles over cellular division cycles, in murines.	– Live-cell time-lapse microscopy	– PS particles were found in the cytoplasm of macrophages, with submicron particles co-localizing with the endoplasmic reticulum and endosomes. – No active excretion of microplastic particles was observed. – Distribution during cell division was cell-specific and depends on the polarization state.	The low cytotoxicity of pristine PS microparticles observed in macrophages may be due to their preferential localization in the cytoplasm, minimizing toxic effects.

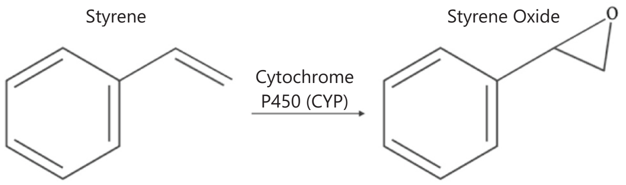

Fig. 2. First step in the styrene metabolism.

compound capable of interacting with DNA, leading to genotoxic effects (Roe, 1994). However, enzymes required for its detoxification are also involved in detoxifying other chemicals, including those naturally occurring in food. However, at high levels of exposure, styrene can exceed the body's capacity to detoxify styrene oxide (SO), resulting in its accumulation and overloading of detoxification pathways such as glutathione conjugation and epoxide hydrolase–mediated hydrolysis (Styrene in Drinking-water Background document for development of WHO Guidelines for Drinking-water Quality, 2003)), which increases the risk of carcinogenicity (Huff & Infante, 2011; Roe, 1994).

The nervous system is highly sensitive to long-term styrene exposure, yet the specific neurotoxic effects of PS-MPs remain poorly understood (Jin et al., 2022a). Reported neurological impacts include neurobehavioral and neurosensory alterations, such as impaired olfaction, hearing, and color discrimination. Notably, the styrene concentrations required to elicit these effects are over 1000 times higher than those typically encountered in the environment (Styrene and Human Health - SIRC, 2024). A recent study shows that exposure to PS-MPs leads to learning and memory dysfunctions and induces neurotoxic effects in mice (Table 2) (Jin et al., 2022b), but the study is restricted to the solid microparticles without considering the likely monomer and oligomers released by the MPs.

Styrene has been evaluated for its potential to cause genetic damage across various animal models, using different endpoints and exposure methods. Generally, styrene does not induce genetic damage even at high concentrations. Some recent studies in rats and mice further confirm these findings, showing no increase in mutagenesis, clastogenesis/aneugenesis, or DNA damage following high oral doses of styrene (Table 2) (Gollapudi, 2023; Styrene and Human Health - SIRC, 2024).

The effects of MP exposure on reproductive systems and fertility in both males and females remain unclear (Wei et al., 2022). Studies in animal models indicate that MPs exposure can cause oxidative stress, hormonal changes, and structural damage in reproductive organs. In males, PS MPs exposure decreased sperm viability and testosterone levels, while in females, it reduced ovarian size and altered hormone levels. These effects were associated with inflammatory processes in gonadal tissues and alterations in reproductive function (Wei et al., 2022). Again, none of these studies went further to know if styrene monomer and oligomers were released from MPs and thus, the real responsibles for the observed damage.

Although PS is frequently mentioned in discussions of microplastic toxicity, it is important to distinguish it from its monomer, styrene, which has a different chemical behavior and toxicological profile. At present, there is no definitive evidence that styrene exposure, whether occupational or environmental, adversely affects fertility, development, or acts as an endocrine disruptor. Research into human fertility has predominantly centered on female fertility, with fewer studies dedicated to male fertility, congenital anomalies, and miscarriages, due to sample limitations, imprecise data on exposure to styrene and possible exposure to other chemicals (Styrene and Human Health - SIRC, 2024).

Emerging evidence from animal and in vitro studies suggests that styrene monomers and oligomers, which crosses the placental barrier, exhibit placental and fetal toxicity with known embryotoxic and fetotoxic effects, but no evidence of teratogenicity (Kersemaekers et al., 1995; Medley et al., 2023). A recent study shows that PS-MPs exposure induces ovarian inflammation and decreases oocyte quality in mice, offering a foundation for investigating the reproductive toxicity mechanisms of PS-MPs in female mammals (Table 2) (Liu et al., 2022). However, it is important to critically assess these findings, as the scientific demonstration of the actual presence of microplastics in biological tissues remains highly challenging. Techniques such as FTIR, Raman spectroscopy, and SEM, while commonly used, have limitations in accurately distinguishing microplastic particles from other materials and substances, such as oligomers. Therefore, the observed toxic effects might not be directly caused by intact PS microplastics, but rather by

Table 2
Summary of styrene toxicity: clinical trials.

Authors/ Year	Study	Methods	Results	Conclusion
(Jin et al., 2022a, 2022b)	BALB/c mice were exposed to drinking water containing 100 μg/l and 1000 μg/l of fluorescent PS-MPs, with diameters of 0.5, 4, and 10 μm for 180 days, to evaluate potential Neurotoxicity from chronic exposure.	– Brain tissues were analyzed for PS-MP accumulation, blood-brain barrier integrity, inflammation, and spine density. – Learning and memory abilities were assessed using the Morris Water Maze (MWM) and novel object recognition tests.	– PS-MPs of all diameters accumulated in the brain tissues. – Disruption of the blood-brain barrier. – ↑ dendritic spine density. – Inflammatory response was noted in the hippocampus. – Cognitive and memory deficits were evident in exposed mice compared to controls.	The outcomes measured here were concentration dependent, but independent of particle size The outcomes measured were concentration dependent, but independent of particle size. Exposure to PS-MPs leads to learning and memory dysfunctions and induces neurotoxic effects in mice.
Gollapudi, 2023	Genotoxicity evaluation in male B6C3F1 mice administered styrene monomer via oral (gavage for 29 consecutive days at doses of 0, 75, 150, or 300 mg/kg/day), using comet, micronucleus, and Pig-a endpoints. Positive controls: ethyl nitrosourea (ENU) and ethyl methanesulfonate (EMS) at specified doses.	– Blood was collected 3 h after the final dose to measure erythrocyte Pig-a mutant and micronucleus frequencies. – DNA strand breakage was evaluated using the alkaline comet assay in glandular stomach, duodenum, kidney, liver, and lung tissues.	– No significant differences in % tail DNA in stomach, liver, lung, and kidney tissues compared to vehicle controls. – Duodenum results were inconclusive due to technical issues. – No significant increases or dose-related trends in Pig-a mutant and micronucleus frequencies.	Oral administration of styrene did not induce DNA damage, mutagenesis, or clastogenesis/ aneugenesis in the tested genotoxicity assays.
Liu et al., 2022	Reproductive toxicity of PS-MPs in female mice after 35 days of continuous exposure.	– Scanning electron microscope (oocyte analysis). – Confocal laser scanning microscope (to observe Green-PS-MPs fluorescence). – Fluorescence spectroscopy (quantify MPs).	– High levels of PS-NPs in heart, liver, spleen, lungs, kidneys, brain, intestines, uterus, and ovaries. – ↓ malondialdehyde (MDA) levels in ovaries. – ↓ glutathione (GSH) levels. – ↓ mitochondrial membrane potential (MMP). – ↓ endoplasmic reticulum calcium ([Ca2+]ER) in oocytes. – ↓ survival rate of superovulated oocytes. – ↑ IL-6 levels in ovaries. – ↑ reactive oxygen species (ROS) in oocytes.	PS-MPs exposure induced inflammation in the ovaries and reduced the quality of oocytes in mice. This suggests that exposure to PS-MPs could cause reproductive toxicity in female mice.

styrene monomers or oligomers released from degraded plastic material. This distinction is essential, as many studies do not clearly differentiate between polymer particles and their chemical derivatives, which can lead to misinterpretation of the exposure source and toxicological mechanism. Unfortunately, most of the publications involving MPs do not consider their solubility in the media. Most of the plastics are not soluble, while monomers and oligomers can be easily dissolved.

Styrene has been shown to be mutagenic in in vitro systems, but only following metabolic activation. In vivo studies reported mutagenic effects, although only at high doses. Its primary metabolite, styrene-7,8-oxide, is a direct-acting mutagen and is likely responsible for the mutagenicity observed after metabolic activation of styrene. While long-term carcinogenicity studies in mice and rats using various administration routes did not demonstrate styrene itself to be carcinogenic, styrene-7,8-oxide exhibited carcinogenicity in prolonged oral studies in rats (Styrene in Drinking-water Background document for development of WHO Guidelines for Drinking-water Quality, 2003).

2.3. *Migration studies*

Migration refers to the transfer of substances from packaging materials to the packaged product. This phenomenon occurs through the diffusion of compounds from regions of higher concentration (the food-contact layer) to regions of lower concentration (the food surface). The diffusion process is influenced by several factors, including the concentration of substances in the packaging and food, the nature of the food, temperature, and the duration of contact between the packaging material and the food. During migration, the substances are absorbed, adsorbed, or dissolved into the food, altering their concentrations in both the packaging and the food (Bhunia et al., 2013).

Typical approaches assume that the mass diffusion between the packaging material and the food can be described by Fick's Second Law:

$$\frac{\partial}{\partial t}C = \frac{\partial}{\partial x}\left(D\frac{\partial}{\partial x}C\right)$$

where C represents the concentration of the migrating species in the packaging material, t represents the time, x the linear dimension of migration and D is the diffusion coefficient of the migrant in the packaging material (Crank, 1975; Poças et al., 2012).

Migration levels of substances from plastics to food under typical use conditions can be estimated through worst-case calculations (assuming 100 % migration), predictive models (diffusion-based), or experimental migration studies using food simulants. Table S3 lists the food simulants currently authorized by the European Union. Migration is generally expressed as mg per dm^2 of plastic or mg per kg of food («Risk Assessment of non-listed substances (NLS) and non-intentionally added substances (NIAS) under Article 19 of Commission Regulation (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food», 2014).

The Regulation (EU) No. 10/2011 (European Commission, 2011) and its amendments specifies detailed testing requirements to assess the migration of styrene (FCM substance No. 193). These methods must simulate the conditions of intended use, such as temperature and time of contact, to ensure accurate safety assessments. The specific simulation conditions for testing the migrants are outlined, ensuring that the tests are relevant to real-world scenarios (European Commission, 2011).

Materials containing styrene must be adequately labelled to inform consumers of any specific conditions or limitations for safe use. The

European regulation 10/2011/EU, which establishes rules for plastic materials intended to come into contact with food, is currently undergoing a major revision (European Commission, 2011). As above mentioned,EFSA recently published a draft scientific opinion concluding that styrene is not genotoxic by oral exposure and that its use in food contact materials would not pose a safety concern if a SML of 40 μg/kg food is applied (EFSA's Re-Assessment of Styrene Safety for Use in Plastic Food Contact Materials, 2025).

The World Health Organization (WHO) previously established a tolerable daily intake (TDI) for styrene of 40 μg per kg of body weight per day (Sadighara, Akbari, et al., 2022). In 2022, WHO reviewed styrene in the context of drinking-water quality and established a TDI of 7.7 μg/kg body weight per day (WHO, 2022). Dietary exposure to styrene from migration in styrenic plastics is estimated at around 0.1 μg/kg body weight (bw) per day, similar to the levels of styrene naturally present in foods. Overall, this combined dietary exposure is similar to or lower than the exposure from inhalation in the general population. Considering human exposure data, a thorough evaluation of genotoxicity, mechanistic studies, comparative toxicokinetics, and interspecies differences is essential to ensure the safety of styrene in food contact materials (FCM). Given the recent EFSA draft opinion proposing a SML of 40 μg/kg food, the market should already anticipate regulatory changes and prepare for compliance with the new SML.

Specific storage and processing conditions, such as temperature fluctuations, should be carefully examined for their influence on styrene migration, since rising temperatures and repeated heating cycles have been shown to significantly increase styrene leaching from polystyrene materials (Ajaj et al., 2021). Prolonged storage time is also critical, because studies of yogurt-packaged polystyrene found that styrene migration increased over time, reaching measurable levels after 50 days of refrigerated storage (Guazzotti et al., 2024). Various food-processing techniques, such as hot-filling, sterilization or thermal treatment, should be analyzed, because real-world dairy products packed in PS that undergo thermal processes show higher styrene levels than simulant tests predict (Guazzotti et al., 2022). Moroever, repeated heating and re-use of polystyrene food containers can significantly increase styrene migration—especially during microwave or dishwasher cycles—and this under-investigated route may pose higher exposure risks than assumed under typical single-use testing conditions (as shown by studies of multiple-use PS cups, e.g., maximum migration after six uses) (Ismail & Hashim, 2008). In addition, oxidized styrene monomer could result from repeated heating PS cups, then, even styrene monomer would not increase the migration values, other derivatives should be under control.

Existing regulatory limits may not fully account for emerging exposure scenarios, such as styrene leaching from microplastics and nanoplastics produced by abrasion in the environment, which warrants further evaluation.

2.3.1. *Analytical techniques*

Over the last few years, numerous studies have focused on evaluating and quantifying the migration of styrene from food packaging into food products. The most employed extraction techniques for determining styrene from PS (polystyrene) are Gas Chromatography coupled with both Mass Spectrometry and a Flame Ionization Detector (P&T/GC/MS + FID), High-Performance Liquid Chromatography (HPLC) and Headspace Solid-Phase Microextraction – Gas Chromatography - Tandem Mass Spectrometry method (HS-SPME-GC–MS/MS) (Table 3).

In 1997, M. Philo, P. Fordham, A. Damant, and L. Castle measured the concentration of styrene-7,8-oxide in nine base resins and sixteen PS samples intended for food contact (Table 3). The epoxide was not detected in the resins (detection limit 0.5 mg/kg) but was present in 11 of the 16 packaging samples, with concentrations up to 2.9 mg/kg. Assuming styrene oxide migrates similarly to styrene monomer, estimated migration levels into food ranged from 0.002 to 0.15 μg/kg. Stability tests in four standard EU food simulants at various temperatures indicated that styrene oxide has a short half-life, particularly in water and aqueous acetic acid, and hydrolyzes to less toxic products, mainly diols. The study concluded that the instability of styrene oxide and its low migration levels make analytical measurements in food unnecessary (Philo et al., 1997).

In 2005, Choi et al. conducted a study evaluating the migration of styrene monomers, dimers, and trimers, highlighting the importance of analyzing oligomers in addition to monomers (Table 3) (Choi et al., 2005). The presence of oligomers, which can also migrate, must be analyzed to understand the full extent of potential contamination. A more recent study by Beneventi et al. in 2022 further expanded on this by examining the migration of styrene monomers, dimers, and oligomers from PS and styrenic copolymers into various simulants (Beneventi et al., 2022). They found that the migration of dimers was generally lower than that of monomers and that both were lower than 50 μg/kg in real food and 20 % ethanol simulants. They found that simulants with a high-fat content caused swelling of the PS, which led to an overestimation of migration levels. Sunflower oil showed greater styrene migration with prolonged exposure or at high temperature, highlighting the influence of these parameters on styrene migration from FCMs (Table 3) and the lack of compatibility of PS with fatty food.

In 2021, a study proposed a method using Gas Chromatography-Mass Spectrometry (GC–MS) to monitor contaminants, including styrene, in honey from plastic food packages. The study concluded that the amount of styrene found in honey depends on the shelf life of the product, which is typically extended by these packages. Thus, the longer shelf life of honey is directly associated with higher levels of styrene (Table 3) (Peñalver et al., 2021).

In the same year, Ajaj et al. Ajaj et al. studied the influence of temperature, food composition, and contact time on the migration of styrene monomer from PS food contact materials into food simulants. Additionally, the Nile Red staining method revealed the migration of both particulate PS, with particle sizes ranging from approximately 1 to 5 μm, and styrene monomer into simulants. These results suggest that high-fat simulants such as 95 % ethanol and isooctane can induce partial disintegration of the PS polymer matrix, raising concerns about potential microplastic ingestion (Ajaj et al., 2021).

In 2022, Guazzotti et al. investigated styrene concentrations in seventeen dairy products packed in PS from the Italian and German markets. The study found that styrene levels ranged from 5 to 30 μg/kg in refrigerated dairy products, while coffee creamer stored at room temperature showed levels up to 401 μg/kg. It concluded that factors such as surface contact area, time/temperature conditions, and fermentation methods significantly influence styrene migration. Furthermore, the study concludes that standardized testing with 50 % ethanol may overestimate migration compared to real food conditions, suggesting the need for revising the compliance testing for PS plastics (Table 3) (Guazzotti et al., 2022).

Kontou et al. developed and validated a rapid HS-SPME-GC–MS/MS method for the determination of styrene in various food matrices. The study measured styrene concentrations in 23 foodstuffs packaged in PS containers and evaluated migration from 14 PS tableware or kitchenware items into different foods. Styrene levels in packaged foods ranged from 0.4 to 160 ng/g, with particularly high concentrations in dairy products intended for children, and the highest migration observed from disposable PS cups containing milk at 70 °C (Table 3)(Kontou et al., 2022).

A recent study assessed styrene levels in PS-packed dairy products from supermarkets and compared them with results from simulated migration tests. (Guazzotti et al., 2023). The study concluded that while the use of 50 % ethanol in testing overestimated migration results due to swelling interactions with PS, testing with 10 % and 20 % ethanol at 40 °C provided higher, yet less extreme, migration levels than those found in real food, and testing at 20 °C yielded results more comparable, but still slightly overestimated, to those in refrigerated dairy products (Table 3) (Guazzotti et al., 2023).

In general, the recent literature indicates that styrene migration is

Table 3
Methods to determine PS as result of its migration from packaging to food simulants or foods.

Authors/Year	FCM	Food or Food Simulant	Extraction Method/ Sample Preparation	Determination Method	Sampling period/place	Levels of migration	Conclusions
Philo et al., 1997	PS articles	Aqueous simulant (sodium chloride solution) Olive oil simulant	Aqueous simulant: Extracted with dichloromethane (1 ml) containing butyl benzoate as an internal standard, using an orbital shaker for 15 min. Olive oil simulant: Diluted 1:1 with hexane and extracted with acetonitrile (10 ml).	GC-FID (Residual styrene oxide) – Mobile phase gas: Helium – Flow of mobile phase: 1 ml/min – Injection volume: 1 μl – Analytical column: 25 m × 0.25 mm capillary column, 0.2 μm wax phase (CPSIL 57CB) – GC temperature program started at 45 °C (1 min) raised at 30 °C/min to 100 °C then at 10 °C/min to 220 °C and held for 5 min GC–MS (Reaction products) detection was conducted in scanning mode between 50 and 250 amu at 1.5 scans/s.	1997, UK	0.002–0.15 μg/kg	The surface of the plastic has lower concentrations of styrene oxide, and its reactivity reduces migration levels due to hydrolysis into less harmful products. Thus, measuring styrene oxide in food is unnecessary.
Choi et al., 2005	PS packaging (styrene monomers, dimers, and trimers)	*n*-heptane and distilled water	Food-grade non-expanded PS discs were exposed to food-simulating solvents in a 40 ml cylindrical glass vial with stainless steel bead spacers, allowing two-sided exposure. Periodic sampling of the simulant was performed using a double-sealing Teflon™ Miniert valve.	GC-FID Monomers: – Mobile phase gas: Nitrogen (N_2) – Flow of mobile phase: 1.6 ml/min – Analytical column: HP-FFAP (50 m × 0.32 mm i.d., 0.50 mm film thickness) – GC temperature program started at 100 °C (1 min) then 3 °C/min to 130 °C – Mode and temperature of injector: splitless 230 °C – Temperature of detector: 250 °C Dimers and Trimers: – Mobile phase gas: Helium – Flow of mobile phase: 1.5 kg/cm^2 – Analytical column: Rtx-5 (30 m × 0.25 mm i.d., 0.25 mm film thickness) – GC temperature program started at 120 °C (5 min), then 10 °C/min to 200 °C and 20 °C/min to 250 °C (10 min). – Mode and temperature of injector: splitless 280 °C – Temperature of detector: 280 °C	2005, Tokyo	– Initial Concentration Monomers: 254 mg/g Dimers: 646 mg/g Trimers: 4756 mg/g – Diffusion Coefficient Monomers: 3.61×10^{-3} (10 °C) 9.45×10^{-3} (24 °C) 3.49×10^{-3} (40 °C) Dimers: 3.32×10^{-3} (10 °C) 9.21×10^{-3} (24 °C) 2.69×10^{-3} (40 °C) Trimers: 2.66×10^{-3} (10 °C) 7.08×10^{-3} (24 °C) 1.65×10^{-3} (40 °C)	Higher temperature yielded a faster migration rate, and larger molecules of the oligomer were slower to reach complete migration. Only styrene trimers migrated to distilled water. The diffusion coefficient of trimers was higher in heptane than in water.
Khaksar & Ghazi-Khansari, 2009	GPPS and HIPS cups to hot drinks	Hot tea, milk, cocoa milk	162 samples were prepared from dry powders reconstituted with boiling distilled water. Extraction was performed using clear	HPLC – Mobile phase: Distilled water (25 %) - Acetonitrile (75 %	2009, Tehran	– GPPS Hot tea: 0.61 to 8.15 μg/l Hot milk: 0.65 to 8.30 μg/l Hot cocoa milk:	Styrene monomer migration at 20 °C is minimal, but when temperature increased, the migration in the

(continued on next page)

Table 3 (*continued*)

Authors/Year	FCM	Food or Food Simulant	Extraction Method/ Sample Preparation	Determination Method	Sampling period/place	Levels of migration	Conclusions
			polystyrene cups (GPPS) and matte polystyrene cups (HIPS), each with a volume of 200 ml and a surface area of 1.2 dm^2.	– Injection volume: 50 µl – Flow rate: 1 ml/min – Detector: UV – λ = 245 nm		0.71 to 8.65 µg/l – HIPS Hot tea: 0.48 to 6.85 µg/l Hot milk: 0.61 to 7.65 µg/l Hot cocoa milk: 0.72 to 7.78 µg/l	first 10 min is considerable, and increases as the time of exposure increases. Migration levels: hot cocoa milk > hot milk > tea
Genualdi et al., 2014	24 PS packaged products	Yogurt, raw chicken, bakery croissants, sandwich cookies, chocolate candies, noodle soup, raw ground beef, chocolate chip cookies, chewing gum	Samples were extracted using 15 ml of ethyl acetate and 1.5 ml of methanol. The polymer was dissolved by vortexing and shaking, then centrifuged. The solution was filtered through 0.2-µm and 0.45-µm PTFE syringe filters, with 7.5 µl of 10,000 mg/kg d8-styrene added as an internal standard.	GC–MS – Mobile phase gas: Helium – Flow of mobile phase: 1 mL/min – Analytical column: Restek Rxi®-5HT (30 m × 0.25 mm i.d., 0.25 µm film thickness) – Stationary phase: Diphenyl dimethyl polysiloxane – Injection volume: 2 µl – Initial inlet temperature: 200 °C, increased to 350 °C at 12 °C/min after 20 min, held for 10 min – Oven temperature program: Initial temperature of 50 °C, ramped by 15 °C/min to 310 °C, followed by a 12 min hold – MS detector conditions: Electron-impact (EI) mode at 70 eV (*m/z* 35–500) – Temperature of detector: 250 °C (ion source), 150 °C (quadrupole), 280 °C (auxiliary zone)	Washington, DC	Monomer: 2.6 to 163 ng/g (food migration) 9.3 to 3100 mg/kg (PS FCMs) Dimers: 130 to 2900 mg/kg (PS FCMs) Trimers: 220 to 16,000 mg/kg (PS FCMs)	Styrene dimers and trimers are present in higher concentrations in PS FCMs than the monomer.
Abolghasemi-Fakhri et al., 2019	Organoclay and zinc oxide nanoparticles (ZnO-NPs)	10 % Ethanol (Aqueous food) 50 % Ethanol (Oil-in-water emulsions)	Simulants: 5 ml of *n*-hexane was added to 20 ml of food simulant in a centrifuge tube, shaken for 20 min, leaving the phase separation at room temperature for over an hour. Samples: 0.25 g of PS sample was dissolved in 10 mL of dichloromethane, then 20 mL of methanol was added to precipitate the polymer. The mixture was left to stand and centrifuged several times. The supernatant was then collected and filtered.	GC–FID – Mobile phase gas: Helium and nitrogen – Flow of mobile phase: 1.8 ml/min – Analytical column: HP-5MS fused silica capillary column – GC temperature program started at 40 °C for 4 min, then 20 °C/min to 120 °C and held for 3 min, followed by 40 °C/min to 280 °C which was held for 5 min – Temperature of injector: 200 °C – Temperature of detector: 200 °C	2019, Iran	- Diffusion Coeficient PS: 7.84 × 10–14 cm^2/s PS/ZnO: 6.13 × 10–14 cm^2/s PS/C15A 4.07 × 10–14 cm^2/s PS/ZnO/C15A: 2.89 × 10–14 cm^2/s	Maximum reduction of SM migration into 10 % and 50 % ethanol (24 h storage at 40 °C) were observed in the polystyrene/nanoclay and polystyrene/ZnO samples, respectively.
Naziruddin et al., 2020	GPPS	Beef soup, curry noodle, pulled tea Simulants: Distilled water, 3 % acetic acid, 10	HS-SPME A carboxen/polydimethylsiloxane (CAR/PDMS) fiber with an 85 µm film thickness was placed in the headspace of a 10 ml vial containing 2 g of sample	GC–MS – Mobile phase gas: Helium – Flow of mobile phase: 1.4 ml/min	Malasya	Beef soup: 0.523 to 0.833 ng/g Curry noodles: 0.523 to 0.668 ng/g Pulled tea: 0.512	The highest styrene levels were found in palm olein and fatty food samples, with migration significantly influenced by fat

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Table 3 (*continued*)

Authors/Year	FCM	Food or Food Simulant	Extraction Method/ Sample Preparation	Determination Method	Sampling period/place	Levels of migration	Conclusions
		% ethanol, palm olein	dissolved in 1.8 ml of saturated NaCl solution. The vial was incubated at 40 °C, with an equilibrium time of 30 min and an extraction time of 15 min. The fiber was then introduced into a GC–MS injector at 250 °C for 10 min.	– Analytical column: DB-5MS, J&W GC column (30 m, 0.25 mm, and 0.25 µm film thickness) – GC program temperature: Initial temperature of 40 °C for 5 min, then ramped at 6 °C/min to 220 °C for 2 min – Injection volume: 1 µl – MS detector conditions: Electron impact (EI) mode, electron energy of 70 eV, selected ion monitoring (SIM) mode – Temperature of detector: 280 °C		to 0.599 ng/g Simulants: 0.538 to 1.781 ng/g	content. All migration levels were below the European Commission's overall migration limit (OML) of 10 mg/dm^2.
Peñalver et al., 2021	PS honey containers	Multifloral honey	1 g of honey was dissolved in 10 ml of water, shaken for 5 min, and filtered through CA (Cellulose Acetate) filters. DLLME 1.5 ml of acetonitrile (disperser solvent) and 175 µl of chloroform (extractant solvent) were injected into the sample solution, creating a cloudy dispersion. After centrifugation for 3 min at 600 *g*, the chloroform droplets sedimented at the bottom of the tube.	GC–MS – Mobile phase gas: Helium – Flow of mobile phase: 1 ml/min – Analytical column: HP-5MS (30 m, 0.25 mm i.d., and 0.25 µm film thickness) – Stationary phase: 5 % diphenyl-95 % dimethylpolysiloxane – GC program temperature: initial temperature of 45 °C for 3 min, increasing to 175 °C at 15 °C/min, followed by a ramp of to 250 °C at 20 °C/min and a final increase to 300 °C – Injection volume: 2 µl – MS detector conditions: electron-impact (EI) mode at 70 eV (m/z 35–500) – Temperature of detector: 230 °C (ion source), 300 °C (transfer line), and 150 °C (quadrupole)	2020, Spain	310 ± 15 ng/g	The higher styrene levels in honey are directly related to the product's extended shelf life.
Ajaj et al., 2021	PS (HIPS, EPS and XPS types)	Simulants: – 10 % Ethanol/ distilled water (Aqueous food) – 3 % Acetic acid (Acidic food) – 50 % Ethanol (Dairy food) – 95 % Ethanol (High fat content)	PS samples were cut into 2–3 cm pieces and immersed in 100 ml of prepared food simulant solutions. After immersion, the solutions were filtered onto polycarbonate membranes. The membranes were stained with Nile Red, dried, and then examined under a microscope to analyze the migration of styrene.	HPLC-FL – Mobile phase: acetonitrile and water (75:25 *v*/v), under isocratic conditions – Injection volume: 50 µl – Flow rate: 1 ml/min (run time of 3 min) λ_{Ex} max = 559 nm, and λ_{Em} max = 636 nm	United Kingdom	Cups: maximum of 0.110 µg/ml Containers: up to 6 µg/ml	Styrene migration is lower in cups compared to food containers. The higher levels in food containers may be due to increased hydrophobicity and testing at higher temperatures. Higher ethanol content (95 %) simulating high fat content also increases styrene migration.
Beneventi et al., 2022	PS	Sunflower oil Créme fraiche Coffee cream	Styrene dimers and trimers are separated. The fractions containing styrene oxide are then directly transferred to	NPLC LC-GC-QqQ – Not reported	–	Sunflower oil:	Elevated migration occurs with higher temperatures and long contact times.

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Table 3 (*continued*)

Authors/Year	FCM	Food or Food Simulant	Extraction Method/ Sample Preparation	Determination Method	Sampling period/place	Levels of migration	Conclusions
			GC in the same mobile phase.			– up to 0.388 mg/kg (70 °C/ 2 h) – up to 0.0643 mg/kg (lower temperature) Créme fraiche: – up to 0.017 mg/kg Coffee cream: – up to 0.123 mg/kg	Coffee cream and crème fraîche show high migration values due to their fatty matrix. Simulants like 95 % EtOH or *n*-heptane overestimate migration due to PS swelling and extraction effects.
Guazzotti et al., 2022	PS dairy-products packaging	Yogurt Cream Sour cream Coffee cream	Aqueous Extraction 5 ml of freshly boiled and cooled down water and 10 μl of an internal standard solution 4.52 ppm of m-xylene were added to each sample after defrosting and shaken for approximately 2 h using a flat bad shaker.	P&T/GC/MS + FID – Mobile phase gas: Helium – Flow of mobile phase: 1 ml/min – Analytical column: Restek RXI 624 MS Sil (60 m length, 0.32 mm inner diameter and1.8 μm film) – Temperature of injector: desorption at 240 °C, with flash heating at 800 °C/s – GC program temperature: 40 °C for 6 min, then a ramp of 5 °C/min to 90 °C, followed by a ramp of 10 °C/min to 260 °C (held for 15 min) – Conditions of detector: full scan mode (35–350 amu) at a scan rate of 0.2 scans/s	2021, Italian and German markets	At BBD – Yogurt (3.5 % fat): 0.5 μg/kg – Cream (30 % fat): 3 μg/kg At the end of shelf life – Refrigerated products: from 5 to 30 μg/kg (in 40 days) – Coffee creamers: 401 μg/kg (6 months)	Higher levels observed in yogurt produced at higher temperatures. Styrene migration is influenced by surface contact area and production/ storage time and temperature.
Kontou et al., 2022	PS foodstuffs containers and tableware/ kitchenware articles made with styrene.	Various foods (water, milk, cheese, cream)	HS-SPME – Not reported	GC–MS/MS – Not reported	2020, Greek market	– Packaged foods: 0.4 to 160 ng/g – Tableware or kitchenware: up to 89 ng/g – Children dairy products: up to 46 ng/g	56 % of PS-packaged dairy products and desserts had styrene >10 ng/g. The highest styrene migration was observed from disposable PS cups filled with milk at 70 °C for 2 h, indicating that styrene migration is maximized under high temperature and prolonged contact conditions.
Guazzotti et al., 2023	PS	Refrigerated dairy products Simulants: 50 % Ethanol 20 % Ethanol 10 % Ethanol	Residual level styrene in the PS packaging: 1 g of the material was extracted with 10 ml of acetone and stored at 60 °C for 3 days. Styrene monomer in food: 1 g of each food was mixed with 5 ml of freshly boiled and cooled-down water and	GC-FID (Residual level styrene in the PS packaging) – Flow of mobile phase: 10 ml/min – Analytical column: ZB 624 – GC temperature program started at 60 °C for 2 min, ramped at 10 °C/min to 250 °C, and held at 250 °C for 5 min.	2022, German supermarket	2.8 to 22.4 μg/kg	50 % ethanol causes exaggerated migration due to PS swelling. 10 % ethanol (40 °C) leads to conservative but less extreme migration than with 50 % ethanol. 20 % ethanol (40 °C) results in conservative

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Table 3 (*continued*)

Authors/Year	FCM	Food or Food Simulant	Extraction Method/ Sample Preparation	Determination Method	Sampling period/place	Levels of migration	Conclusions
			spiked with an internal standard solution of styrene d-8.	– Temperature of injector: 110 °C (needle temperature) – Temperature of detector: 120 °C (transfer line) P&T/GC/MS + FID (Styrene monomer in food) – Mobile phase gas: Helium – Flow of mobile phase: 20 ml/min (purge flow rate for the headspace) – Analytical column: Restek RXI-624 MS Sil (60 m × 0.32 mm × 1.8 μm film) – Temperature of injector: 250 °C – GC program temperature: Initial temperature of 40 °C for 6 min, then increased by 5 °C/min to 90 °C, followed by an increase of 10 °C/min to 260 °C for 15 min – Conditions of detector: MS operating in full scan mode (35–350 amu) at 0.2 scans/s; monitored ions are m/z 104 for styrene and m/z 112 for styrene d-8. A splitter separates eluting substances 1:1 to MS and FID			migration levels, still higher than real food.

PS: Polystyrene | **IS:** Internal Standard | **GC-FID:** Gas Chromatography with Flame Ionization Detection | **GC–MS:** Gas Chromatography-Mass Spectrometry | **GPPS:** General Purpose Polystyrene | **HIPS:** High Impact Polystyrene | **HPLC:** High-Performance Liquid Chromatography | **DLLME:** Dispersive Liquid-Liquid Microextraction | **HS-SPME-GC–MS:** Headspace Solid-Phase Microextraction Gas Chromatography-Mass Spectrometry | **HPLC-FL:** High-Performance Liquid Chromatography with Fluorescence Detection | **NPLC:** Normal Phase Liquid Chromatography | **LC-GC-QqQ:** Liquid Chromatography-Gas Chromatography Triple Quadrupole Mass Spectrometry | **P&T/GC/MS + FID:** Purge and Trap Gas Chromatography-Mass Spectrometry with Flame Ionization Detection.

influenced by various factors. Foods with extended shelf lives, such as honey, often show higher levels of styrene migration compared to perishable items like dairy products. This phenomenon is due to prolonged contact time between the food and the packaging material, which allows for a greater quantity of styrene to migrate into the food. Higher temperatures also accelerate the diffusion process, as expected, thereby enhancing the migration of styrene from the FCMs into the food product. Foods with high fat content also tend to exhibit higher migration rates. This is attributed to the affinity of fatty substances for styrene, which facilitates its transfer from the packaging material into the food (Sadighara, Akbari, et al., 2022). Lastly, the use of fatty food simulants with high concentrations of ethanol leads to overestimate migration of styrene. This occurs because these simulants cause swelling of the plastic material, which enhances the migration of styrene (Guazzotti et al., 2023).

Certain food processing techniques, such as high-temperature treatments or irradiation, can increase styrene migration into food products, as the material undergoes slight decomposition, releasing styrene. Irradiation is a food processing technique that uses ionizing radiation to inactivate food spoilage organisms, including bacteria, molds, and yeasts and it is permitted in Europe for being applied only on spices. It is usually applied on packaged food and it is effective in extending the shelf life of fresh fruits and vegetables by controlling biological changes associated with ripening, maturation, sprouting, and aging. While irradiation enhances food safety and prolongs the shelf life of food, it can also alter food packaging, particularly plastics (Félix et al., 2008; Salafranca et al., 2015), leading to chemical changes that may increase the migration of substances like styrene into food. Therefore, the use of irradiation must be carefully controlled to avoid unwanted effects.

Research indicates that styrene-d8 is the most used internal standard in styrene migration studies due to its effective isotopic labeling, which enhances accuracy in quantification and reduces analytical interferences, specially when using MS as detector (Genualdi et al., 2014). Its widespread use ensures reliable and consistent results across various research studies.

The determination of styrene has recently evolved significantly with the adoption of more advanced and sensitive techniques. High-resolution mass spectrometry (HRMS) has become an important tool for providing accurate information on the mass fragments, enabling the reliable identification of analytes at very low concentrations. Traditional methods such as GC–MS and LC-MS continue to be widely used but have been enhanced with advanced sampling techniques such as SPME and solid phase extraction (SPE), which improve the concentration and purification of analytes (Kontou et al., 2022).

Recently, there has been a clear shift towards the use of green chemistry extraction techniques, reflecting a growing concern for sustainability in analytical methodologies. These approaches prioritize the reduction of solvent use, as happens in SPME, or the substitution of conventional solvents with more sustainable alternatives such as water and ethanol, thereby promoting cleaner, more efficient, and environmentally friendly extractions.

Another crucial aspect to consider is that, while numerous studies focus on the migration of substances from packaging into food, it is equally imperative to evaluate the potential health risks posed by the ingestion of styrene through food. A comprehensive safety assessment of styrene and its derivatives must account for both the migration process and the broader implications for human health, ensuring a holistic understanding of their effects. It is true that the aggregate data from various studies indicate that the average styrene levels found in food are below the regulatory limits. This suggests that, all parameters above mentioned that affect the migration of styrene effectively ensure that styrene concentrations remain within acceptable thresholds (Pilevar et al., 2019). However, although migration levels in these studies did not exceed the safety limits established by European Union legislation No. 10/2011 (OML of 10 mg/dm^2), cumulative exposure to styrene from food packaging and other sources should not be overlooked.

In sum, techniques such as headspace gas chromatography–mass spectrometry (HS-GC–MS), solid-phase microextraction coupled with GC–MS (SPME-GC–MS) and LC-MS/MS are widely recognized for their precision, low detection limits, and suitability for volatile organic compounds like styrene. Additionally, methods validated according to international guidelines and the participation in PT schemes ensures reproducibility and comparability across studies. In 2019 a PT assessed the proficiency of National Reference Laboratories and Official Control Laboratories in quantifying styrene in milk at the proposed new SML for a future amendment to Commission Regulation (EU) No 10/2011, demonstrating strong analytical capability with over 80 % satisfactory z-scores (Beldi et al., 2024). When dealing with recycled packaging, where additional contaminants or decomposition products may interfere, robust sample-cleaning steps and the use of selective mass-spectrometric detection become essential to accurately distinguish styrene and its seven known oligomers from other co-migrants. Such methodological detail is critical for ensuring reliable exposure assessments and regulatory compliance. Recent publications demonstrate that styrene monomer diminishes in the recycling process, as the oxidized styrene is formed (Guazzotti et al., 2023). This fact opens new work on the toxicity of resulting compounds from the recycling step.

3. Recycling of polystyrene: most used techniques

Packaging is an essential component of the food sector; however, plastic waste represents one of the most pressing environmental challenges facing humanity (Xu et al., 2022).

Recycling PS remains a major challenge due to the high costs of mechanical and chemical recycling methods and limited economic feasibility. Catalytic depolymerization of PS offers a promising alternative, as the use of a catalyst can enhance product selectivity, facilitating the chemical recycling and upcycling of PS. (Marquez et al., 2023; Xu et al., 2024).

A recent study examined co-extruded yogurt cups with an artificially spiked core layer to assess the migration of surrogate substances. The study concluded that, although the high processing temperatures during co-extrusion caused partial contamination of the virgin PS functional barrier layer, using post-consumer recycled PS (rPS) behind a virgin PS functional barrier can still be considered safe under the evaluated conditions (Welle, 2023).

3.1. Mechanical recycling

Mechanical recycling is the most widely used method for processing plastics such as polyethylene terephthalate (PET) and high-density polyethylene (HDPE), commonly found in soft drink bottles and containers. This method transforms plastic waste into secondary raw materials or products while preserving the original chemical structure of the material (Fig. 3). By efficiently reprocessing plastic waste, mechanical recycling helps reducing the demand for new plastic production, thus supporting sustainability (Recycling technologies • Plastics Europe, 2024) and providing a new life to the plastic.

3.2. Dissolution

PS can be easily recycled using dissolving technology, where a selective solvent quickly dissolves polystyrene from mixed plastic waste with high efficiency, without affecting other materials present (Fig. 3). This process ensures that the properties of the rPS are preserved, exhibiting the same characteristics as those of the virgin material. The deep purification of rPS effectively treats impurities and high coloring, making it suitable for high-quality applications, including food contact (Circular Solutions, 2024).

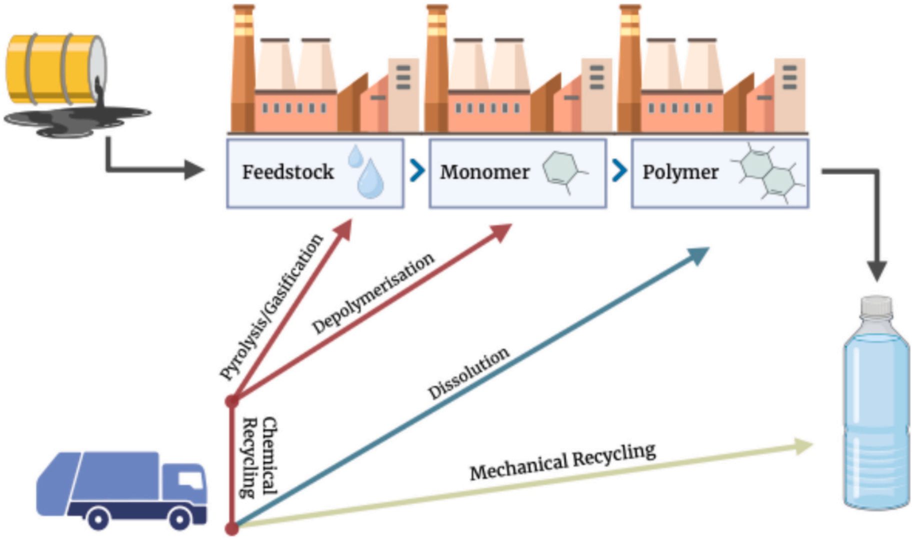

Fig. 3. Overview of plastic recycling methods (created with biorender.com). this figure is adapted from plastics europe: chemical recycling. (Chemical recycling • Plastics Europe, 2024).

3.3. Chemical recycling

Chemical recycling is an emerging technique that provides significant scalability potential. Chemical recycling technologies alter the chemical structure of polymer waste to transform it into basic chemicals or other feedstocks that can be used as raw materials for new plastics or products (Fig. 3) (Chemical Recycling • Plastics Europe, 2024; Rizos et al., 2023).

With 67.5 % of post-consumer plastic waste going to landfill, chemical recycling has emerged as an effective solution for plastics that would otherwise be incinerated or sent to landfill. Moreover, chemical recycling enables the production of recycled plastics with properties equivalent to those of virgin materials, making them suitable for applications demanding high quality and safety standards, such as food-contact uses (Chemical Recycling • Plastics Europe, 2024).

3.3.1. Catalytic depolymerization

Polystyrene is ideally suited for chemical recycling in the form of depolymerization, which converts polystyrene packaging waste back into its original liquid monomer (Fig. 3). This recycled monomer can be re-polymerized into high-quality rPS or used in other styrenic polymers (Circular Solutions, 2024). Depolymerization is efficient due to polystyrene's low ceiling temperature and liquid monomer state, simplifying the recycling process and purification. Unlike other methods that involve additional steps like cracking, depolymerization goes directly from polymer to monomer. This method supports near-infinite recycling cycles, maintaining the material's properties and ensuring suitability for repeated use. rPS produced this way is identical to virgin polystyrene, allowing its use in high-quality applications, including food contact (Circular Solutions, 2024).

Catalysts play a crucial role in achieving efficient depolymerization. Among metal oxides, calcium oxide has been identified as both the most cost-effective and efficient catalyst. Metal carbonates can produce pure styrene, but only in low yields. In contrast, acids are poor catalysts for depolymerization, as they promote side reactions that generate undesired products. It has been demonstrated that basic catalysts favor polystyrene decomposition through a selective depolymerization pathway, whereas solid acids tend to direct the reaction towards pathways producing compounds other than styrene (Marczewski et al., 2013).

3.4. Down-cycling

Downcycling refers to the process of converting waste materials into products of lower value, often for use as energy sources rather than reusable raw materials.

In pyrolysis, plastic waste is heated to temperatures above 400 °C under low-oxygen conditions, breaking down long polymer chains into simpler hydrocarbon products (Chemical Recycling Explained: An Overview | Pryme, 2024). In gasification, mixed waste is subjected to extremely high temperatures (1000 °C to 1500 °C) with a limited supply of oxygen, reducing the material to its basic molecular components and producing synthesis gas (syngas), a mixture of hydrogen and carbon monoxide (BPF, 2024). Hydrocracking is a catalytic refining process that uses hydrogen to breakdown, in a single stage, heavy polymer molecules into much lighter and valuable molecules in the gaseous and liquid ranges, like diesel, jet fuel, or base chemicals (Costa et al., 2024), which will be further used for different industrial applications.

3.5. Circular economy

The main objective is to transition the food packaging sector from a linear to a circular economy (Welle, 2023). The circular economy of plastics aims to create a closed cycle in which plastic is continually reused, recycled, or composted, minimizing waste and the need to produce new materials (European Commission, 2015; Johansen et al., 2022).

PS is an excellent recyclable material, enabling closed-loop recycling into food contact applications and maintaining a positive environmental footprint. It effectively preserves food, extends shelf life, and reduces waste due to its durability. Additionally, its lightweight nature reduces transportation costs and emissions, and its insulation properties are beneficial for maintaining food temperature. Polystyrene's ease of processing and versatility in design further support its role in a circular economy, enhancing recycling and reuse rates (Circular Solutions, 2024).

EU regulations target recycling 50 % of plastic packaging waste by 2025 and 55 % by 2030, aiming for all plastic packaging to be reusable or recyclable by 2030 (Circular Solutions, 2024; European Commission, 2015). The styrene sector supports these goals and highlights PS as a significant contributor due to its fully recyclable nature and alignment with EU circular economy targets, thereby enhancing recycling and reuse rates (Circular Solutions, 2024).

3.5.1. Upcycling

Upcycling, the process of converting waste materials, by-products, or unwanted products into new materials or items with higher value, quality, or functionality, has been proposed to address the low profitability and market sensitivity of conventional recycling methods. Current upcycling approaches, however, are energy-intensive and rely on precious-metal catalysts, typically yielding low-value oligomers, monomers, and common aromatic compounds (Xu et al., 2022).

A recent study evaluated a cascade degradation-upcycling strategy to convert PS waste into high-value chemicals with high selectivity. The process involves first degrading PS waste into aromatics using ultraviolet light, followed by upcycling these intermediates into diphenylmethane. Both reactions are catalyzed by low-cost $AlCl_3$ at room temperatures and atmospheric pressure (Xu et al., 2022).

These innovative approaches serve as a significant alternative to traditional recycling methods by utilizing low-cost catalysts and ambient conditions, offering more sustainable and economically viable solutions.

4. Conclusions and future perspectives

Food packaging has advanced considerably in recent decades, playing a vital role in preserving food and extending shelf life. However, the potential migration of substances from packaging into food—arising from degradation, interactions, or impurities in raw materials—remains a significant concern.

Styrene, a key monomer in polystyrene and related polymers, offers advantages such as versatility, lightweight properties, and cost-effectiveness. Nevertheless, there is increasing concern about residual styrene migrating from PS packaging into food. This migration is influenced by the quality of the packaging, food composition, and storage conditions, and can be further exacerbated by food processing methods such as high-temperature treatments or irradiation.

Recent studies show that extended contact between food and packaging, elevated storage temperatures, and higher fat content in food all increase styrene migration. Additionally, fatty food simulants with high ethanol concentrations can lead to overestimated migration due to their swelling effect on plastic, further enhancing styrene transfer. Styrene concentrations in different foods differ, but the general trend indicates that the risk of migration increases with prolonged exposure to the packaging material, particularly under high-temperature conditions.

Concerning the exposure to styrene, there is a lack of sufficient clinical research on the adverse health effects of styrene and this situation calls for wider clinical trials. Some studies have pointed to certain health hazards arising from exposure to styrene, mainly during inhalation or ingestion of materials like food containers, but most available evidence has been from animal or occupational exposure studies carried out at industrial level. Emerging evidence directly on the effects of such exposure on human health of the general population, and more so on chronic, low dose exposures normally experienced in daily life, is scarce. Clinical trials are needed to help fill in these gaps by evaluating the ways and extent (and rate) of absorption, distribution, metabolism, and excretion of styrene in people and potential health effects e.g. on respiratory or nervous systems, cancer, among others. Detailed clinical information would improve the appropriateness of regulatory efforts, lowering risks from styrene through the establishment of better and lower tolerable exposure levels. Considering the fact that styrene is nowadays very commonly used in many consumer products, such studies are very important in determining the safety and/or continued use of styrene.

Additionally, the increasing use of plastics exacerbates environmental issues, as improper disposal and accumulation of plastic waste contribute significantly to pollution and ecological damage. In this regard, transitioning to a circular economy is essential. Innovations in technology and recycling methods are crucial for significantly increasing the reuse and recycling of packaging materials by, for example, creating more recyclable products and more innovative recycling techniques. For instance, chemical recycling offers a promising pathway for reducing waste and contributing to a circular economy for plastics. It has been demonstrated that polystyrene can be effectively depolymerized to recover styrene monomer, maintaining the material's original properties while making it fully recyclable.

Furthermore, creating recyclable products and implementing more innovative recycling techniques, along with a supportive policy and regulatory framework, are key steps in this transition. This framework should promote chemical recycling, harmonize collection processes, and stimulate investment in the market for secondary raw materials. Achieving high profitability and low market sensitivity is essential to enhance incentives for recycling plastics, particularly those at the end of their life cycle. This approach ensures that food packaging not only maintains its role in preserving food quality but also supports environmental sustainability through efficient waste management and reduced plastic pollution.

Periodic updates and harmonization of global safety standards for styrene in food packaging are crucial to ensure that regulatory frameworks remain aligned with rapidly evolving industrial practices and technological developments. As new packaging materials, such as recycled polymers, bio-based alternatives, and advanced multilayer structures, enter the market, they may exhibit different migration behaviours that are not adequately covered by outdated regulations or standardized test conditions. Additionally, improvements in analytical techniques, now capable of detecting styrene and their oligomers and derivatives at much lower concentrations in complex matrices, require the update ofrexisting limits and validation requirements to ensure they reflect current scientific capabilities. Without regular revision and international alignment, inconsistencies may arise between regions (Nerin et al., 2025), creating regulatory gaps that hinder enforcement and potentially expose consumers to unnecessary risk. Harmonized, science-based updates strengthen global consumer protection by ensuring that safety thresholds, testing protocols, and risk assessment methodologies remain relevant, comparable, and effective across diverse markets.

In conclusion, while current data show that styrene levels in food remain within regulatory limits, future research should focus on the cumulative exposure to styrene from both food packaging and other environmental sources. As packaging materials and food processing methods evolve, continuous monitoring and updates to safety standards may be necessary to ensure long-term consumer safety. Lastly, the shift towards a Circular Economy is vital to achieving safer and more sustainable packaging solutions for the future. Future research should also prioritize the development and validation of bio-based or biodegradable packaging materials with inherently low styrene content, thereby supporting safer food-contact solutions and advancing circular-economy objectives.

CRediT authorship contribution statement

Tatiana Gonçalves Norte: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Fernando Ramos:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Cristina Nerín:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Conceptualization. **Ana Sanches Silva:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Given Ana Sanches Silva role as Editor of Food Chemistry, Ana Sanches Silva had no involvement in the peer-review of this article and has no access to information regarding its peer-review.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2025.147512.

Data availability

Data will be made available on request.

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