

Physicochemical Properties and Styrene Migration Potential of Polystyrene Food Packaging

Edirin Awana

Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

Oyeyemi Adeyemi

Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

Olalekan Adeyemi

adeyemi.olalekan@fupre.edu.ng

Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

Research Article

Keywords: Polystyrene, Styrene migration, Food packaging, SEM–EDS, FTIR, Thermal analysis, HPLC, Food-contact materials

Posted Date: July 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10309529/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Polystyrene (PS) is extensively used in food packaging owing to its lightweight nature, thermal insulation, and low production cost; however, concerns remain regarding styrene migration into foods under different storage conditions[1]. This study integrated physicochemical characterization with migration analysis to evaluate the structural stability and styrene release potential of commercial PS food packaging. Surface morphology and elemental composition were determined by scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDS), while thermal behaviour was assessed using differential scanning calorimetry (DSC), differential thermal analysis (DTA), and thermogravimetric analysis (TGA). Functional groups were identified by Fourier transform infrared spectroscopy (FTIR), and styrene migration into distilled water, 10% ethanol, 3% acetic acid, and vegetable oil at 25, 40, and 70°C was quantified by high-performance liquid chromatography (HPLC). SEM–EDS revealed carbon as the predominant element (83.25 wt%; 90.33 at%), confirming the polymeric carbon-rich matrix. FTIR spectra exhibited characteristic aromatic and aliphatic functional groups of polystyrene, while DSC identified a major thermal transition at 87.01°C. TGA demonstrated excellent thermal stability, with negligible mass loss below 250°C and principal degradation occurring above 300°C. HPLC analysis showed temperature-dependent styrene migration, with the highest concentration observed in 10% ethanol at 70°C (128.6 ± 5.4 µg/L), followed by distilled water at 40°C (68.9 ± 3.2 µg/L) and distilled water or 10% ethanol at 25°C (18.3 ± 1.2 µg/L). Retention times remained consistent (5.41–5.43 min), indicating analytical reliability. These findings demonstrate that although the packaging possesses high structural and thermal integrity, elevated temperatures and food simulant composition significantly enhance styrene migration, emphasizing the need for appropriate temperature management to minimize consumer exposure.

Introduction

Food packaging has evolved from serving merely as a protective barrier to becoming an essential component of modern food preservation, transportation, marketing, and safety assurance [2]. Among synthetic packaging materials, polystyrene (PS) remains one of the most extensively used polymers because of its low density, rigidity, excellent thermal insulation, ease of processing, and cost-effectiveness [3]. These characteristics have made PS the material of choice for disposable cups, takeaway food containers, meat trays, dairy products, and numerous ready-to-eat food packages [3]. Despite these technological advantages, increasing scientific attention has focused on the ability of food-contact polymers to release low-molecular-weight constituents into foods during storage and use, raising concerns regarding long-term consumer exposure.

Polystyrene is synthesized through the polymerization of styrene monomer[4]. Although polymerization is highly efficient, residual styrene monomer, oligomers, and processing-related additives may remain entrapped within the polymer matrix after manufacture [5]. These compounds may subsequently migrate into foods through diffusion-driven processes that are influenced by polymer characteristics, food composition, storage duration, surface-area-to-volume ratio, and environmental conditions, particularly

temperature [6]. Migration is fundamentally a physicochemical phenomenon governed by concentration gradients and molecular mobility within the polymer network. Elevated temperatures increase polymer chain mobility and diffusion coefficients, while certain food matrices, especially those containing organic solvents, fats, or acidic constituents, enhance the partitioning of migrants from the polymer into food. Consequently, migration is not solely a function of residual monomer concentration but also reflects the interaction between polymer structure and the physicochemical properties of the contacting food [7].

Among the substances associated with PS packaging, styrene has attracted considerable scientific and regulatory interest because of its widespread occurrence in food-contact materials and the continuing evaluation of its oral safety [8]. Regulatory authorities and researchers have increasingly emphasized the importance of generating reliable migration data under realistic and worst-case conditions to support exposure assessment and risk management [9], [10]. Recent regulatory evaluations have further highlighted the need for comprehensive migration studies capable of linking material properties with chemical release behaviour, while proposed migration limits continue to stimulate research into the factors governing styrene transfer from packaging materials to foods [8].

Current investigations of styrene migration have demonstrated that migration behaviour varies considerably with food type, storage temperature, contact time, and the physicochemical characteristics of the packaging material [11]. Most published studies have concentrated primarily on quantifying migrated styrene in specific food products or simulants [8], [12], [13]. While these investigations provide valuable exposure data, relatively few studies have comprehensively integrated structural characterization of commercial PS food packaging with detailed thermal analysis and systematic evaluation of styrene migration under multiple storage conditions [14]. Such integration is scientifically important because the migration behaviour of a polymer cannot be fully understood without first establishing the structural, elemental, thermal, and chemical characteristics that govern molecular diffusion within the polymer matrix. The relationship between polymer integrity and migrant release therefore remains insufficiently characterised for many commercially available food packaging materials.

Comprehensive physicochemical characterization using complementary analytical techniques provides valuable insight into the mechanisms controlling migration [15]. Scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDS) elucidates surface morphology and elemental composition, Fourier transform infrared spectroscopy (FTIR) identifies characteristic functional groups and confirms polymer identity, while differential scanning calorimetry (DSC), differential thermal analysis (DTA), and thermogravimetric analysis (TGA) collectively evaluate thermal transitions, decomposition behaviour, and overall material stability. When these techniques are combined with high-performance liquid chromatography (HPLC) for styrene quantification, a holistic understanding of the relationship between polymer structure and migration behaviour can be achieved. Such an integrated analytical framework provides stronger mechanistic evidence than migration testing alone and supports more informed evaluations of packaging safety and performance.

The present study was therefore designed to integrate physicochemical characterization with migration analysis to evaluate the structural integrity, thermal behaviour, chemical composition, and styrene release potential of commercial polystyrene food packaging. SEM–EDS, FTIR, DSC, DTA, and TGA were employed to characterize the material, while HPLC was used to quantify styrene migration into distilled water, 10% ethanol, 3% acetic acid, and vegetable oil at 25, 40, and 70°C. By establishing the relationship between intrinsic material properties and temperature-dependent migration behaviour, this study provides mechanistic evidence that enhances understanding of styrene release from PS food packaging and contributes scientifically relevant data for food-contact material safety assessment, exposure evaluation, and future packaging design.

Materials and Methods

Sample Collection

Commercially available white expanded polystyrene (EPS) food packaging containers commonly used for takeaway meals were obtained from retail vendors in Delta State, Nigeria. The samples were selected based on their widespread use for packaging hot foods and beverages. Prior to analysis, all samples were visually inspected to ensure the absence of cracks, discoloration, or physical defects. The packaging materials were washed with deionized water, air-dried under laboratory conditions, and stored in clean polyethylene bags until characterization and migration experiments were performed.

Chemicals and Reagents

Analytical-grade styrene standard ($\geq 99.5\%$ purity), HPLC-grade methanol, acetonitrile, ethanol, glacial acetic acid, and n-hexane were used throughout the study. Ultrapure distilled water ($18.2 \text{ M}\Omega\cdot\text{cm}$) was produced using a laboratory water purification system. All chemicals and reagents were of chromatographic grade and were used without further purification.

Physicochemical Characterization of Polystyrene Packaging

Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM–EDS)

The surface morphology and elemental composition of the polystyrene packaging material were examined using a Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Spectroscopy (EDS) detector. Small sections (approximately $10 \times 10 \text{ mm}$) were mounted on aluminium stubs using conductive carbon tape and sputter-coated with a thin layer of gold to enhance conductivity. Micrographs were obtained at appropriate accelerating voltages and magnifications to evaluate surface texture, pore distribution, and structural homogeneity. Elemental composition was determined by EDS and reported as both atomic and weight percentages.

Differential Scanning Calorimetry (DSC)

Thermal transition behaviour of the packaging material was determined using Differential Scanning Calorimetry (DSC). Approximately 5–6 mg of finely cut sample was sealed in a standard aluminium pan, while an empty sealed pan served as the reference. Samples were heated from 35 to 250°C at a constant heating rate of 10°C min⁻¹ under a nitrogen atmosphere. The onset temperature, transition peak, recovery temperature, equilibrium temperature, and thermal events associated with polymer relaxation were recorded.

Fourier Transform Infrared Spectroscopy (FTIR)

Functional groups present in the polymer matrix were identified using Fourier Transform Infrared Spectroscopy (FTIR). Spectra were recorded within the range of 4000–400 cm⁻¹ using attenuated total reflectance (ATR) mode with a spectral resolution of 4 cm⁻¹ and 32 accumulated scans per sample. Characteristic absorption bands were assigned according to standard infrared spectral libraries for polystyrene.

Differential Thermal Analysis (DTA)

Differential Thermal Analysis (DTA) was performed simultaneously with thermogravimetric measurements to evaluate the thermal transitions of the packaging material. Samples were heated under nitrogen atmosphere from ambient temperature to 600°C at a heating rate of 10°C min⁻¹. Endothermic and exothermic transitions, glass transition temperature (T_g), decomposition onset temperature, and maximum degradation temperature were determined from the resulting thermograms.

Thermogravimetric Analysis (TGA)

Thermal stability and degradation characteristics of the polystyrene packaging were investigated using Thermogravimetric Analysis (TGA). Approximately 5 mg of sample was heated from ambient temperature to 600°C under a continuous nitrogen flow at 10°C min⁻¹. Percentage weight loss, residual mass, degradation stages, initial decomposition temperature (IDT), and temperatures corresponding to 5% and 10% weight loss (T₅ and T₁₀) were determined from the thermograms.

Styrene Migration Experiment

Migration studies were conducted in accordance with internationally accepted protocols for food-contact materials using standard food simulants representing different food categories[16]. Four simulants were employed:

- Distilled water (aqueous foods)

- 3% (v/v) acetic acid (acidic foods)
- 10% (v/v) ethanol (hydrophilic foods)
- Refined vegetable oil (fatty foods)

Equal-sized pieces of polystyrene packaging (approximately 5 × 5 cm) were immersed individually in 100 mL of each food simulant contained in amber glass bottles with Teflon-lined screw caps. The samples were incubated under three storage conditions representing ambient, moderate heating, and high-temperature food contact:

● 25°C

- 40°C

● 70°C

Each exposure lasted for 2 h to simulate typical consumer use conditions. After incubation, the simulants were allowed to cool to room temperature where necessary and were filtered through 0.45 µm PTFE membrane filters before chromatographic analysis.

Determination of Styrene by High-Performance Liquid Chromatography (HPLC)

Styrene concentrations in the food simulants were quantified using High-Performance Liquid Chromatography (HPLC) equipped with a UV detector. Chromatographic separation was achieved using a reverse-phase C18 analytical column maintained at ambient temperature.

The mobile phase consisted of acetonitrile and water operated under isocratic conditions at a flow rate of 1.0 mL min⁻¹. Twenty microlitres of each sample were injected into the chromatographic system. Styrene was monitored at its maximum UV absorption wavelength of 245 nm. Quantification was performed using an external calibration curve prepared from certified styrene standards covering the concentration range expected in the migration experiments. Peak identification was confirmed by comparison of retention times with authenticated standards.

Quality Assurance and Quality Control

All analyses were performed in triplicate. Glassware was thoroughly cleaned with detergent, rinsed with deionized water, and finally rinsed with HPLC-grade methanol prior to use. Procedural blanks were included during sample preparation to eliminate potential laboratory contamination. Instrument calibration was verified before each analytical batch using freshly prepared calibration standards. Replicate analyses were accepted only when the relative standard deviation was below 5%.

Statistical Analysis

Experimental data were expressed as mean $\pm$ standard deviation (SD) of three independent determinations. Statistical analyses were performed using IBM SPSS Statistics version 27. One-way analysis of variance (ANOVA) was used to evaluate differences among migration conditions, followed by Tukey's honestly significant difference (HSD) post hoc test for multiple comparisons. Statistical significance was established at $p < 0.05$.

Results

SEM–EDS Characterization of the Polystyrene Food Packaging Material

SEM–EDS analysis confirmed that the packaging material was predominantly composed of carbon, with atomic and weight concentrations of 90.33% and 83.25%, respectively (Table 1A), consistent with the carbon-rich structure of polystyrene. Nitrogen was the second most abundant element, accounting for 6.26% atomic concentration and 6.72% by weight. Trace quantities of silicon (0.92% atomic; 1.98 wt%), iron (0.71% atomic; 3.06 wt%), calcium (0.57% atomic; 1.75 wt%), magnesium (0.42% atomic; 0.78 wt%), aluminium (0.39% atomic; 0.80 wt%), manganese (0.22% atomic; 0.95 wt%) and vanadium (0.18% atomic; 0.72 wt%) were also detected, whereas phosphorus, sulfur, chlorine, sodium, potassium and titanium were not detected. Based on elemental abundance (Table 1B), carbon constituted the principal structural component of the polymer matrix, while nitrogen was identified as a secondary constituent. The remaining detected elements occurred only at trace levels and are indicative of minor inorganic constituents associated with commercial polymer manufacture. Iron exhibited the highest weight percentage among the trace elements (3.06 wt%), followed by silicon (1.98 wt%) and calcium (1.75 wt%). Overall, the elemental profile (Table 1C) demonstrated that the packaging material consisted of a carbon-dominated polymer matrix with only minor inorganic constituents. The predominance of carbon, together with the absence of detectable hazardous heavy metals and chlorinated components, confirms the characteristic elemental composition of commercial polystyrene food packaging.

Table 1
A. Elemental Composition of Polystyrene Food Packaging Material Determined by SEM-EDS Analysis

Element	Atomic Number	Atomic Concentration (%)	Weight Concentration (%)
Carbon (C)	6	90.33	83.25
Nitrogen (N)	7	6.26	6.72
Silicon (Si)	14	0.92	1.98
Iron (Fe)	26	0.71	3.06
Calcium (Ca)	20	0.57	1.75
Magnesium (Mg)	12	0.42	0.78
Aluminium (Al)	13	0.39	0.80
Manganese (Mn)	25	0.22	0.95
Vanadium (V)	23	0.18	0.72
Phosphorus (P)	15	ND	ND
Sulfur (S)	16	ND	ND
Chlorine (Cl)	17	ND	ND
Sodium (Na)	11	ND	ND
Potassium (K)	19	ND	ND
Titanium (Ti)	22	ND	ND

ND = Not Detected.

Table 1
B. Major and Trace Elements Identified in Polystyrene Food Packaging Material

Classification	Element	Atomic Concentration (%)	Weight Concentration (%)	Possible Origin
Major Element	Carbon (C)	90.33	83.25	Polystyrene polymer backbone
Secondary Element	Nitrogen (N)	6.26	6.72	Additives, surface contamination, or processing residues
Trace Element	Iron (Fe)	0.71	3.06	Manufacturing equipment contamination
Trace Element	Silicon (Si)	0.92	1.98	Fillers or processing aids
Trace Element	Calcium (Ca)	0.57	1.75	Stabilizers or mineral additives
Trace Element	Manganese (Mn)	0.22	0.95	Processing residues
Trace Element	Aluminium (Al)	0.39	0.80	Manufacturing additives
Trace Element	Magnesium (Mg)	0.42	0.78	Mineral impurities
Trace Element	Vanadium (V)	0.18	0.72	Trace industrial contamination

Table 1
C. Summary of SEM–EDS Characterization of Polystyrene Food Packaging Material

Parameter	Observation	Interpretation
Dominant element	Carbon (83.25 wt%)	Confirms organic polymeric nature
Carbon content	Very high	Consistent with polystyrene composition
Nitrogen presence	6.72 wt%	May originate from additives or environmental exposure
Metallic elements detected	Fe, Mn, Al, V	Trace contaminants or manufacturing residues
Mineral elements detected	Si, Ca, Mg	Possible fillers or stabilizers
Hazardous heavy metals	Not detected at significant levels	Indicates relatively low inorganic contamination
Overall composition	Carbon-rich polymer matrix with minor inorganic constituents	Typical of commercial polystyrene food packaging

Differential Scanning Calorimetry (DSC)

The DSC thermogram (Table 2A) revealed a characteristic thermal transition for the polystyrene packaging material over the investigated temperature range of 35.01–250.55°C. Thermal activity commenced at an onset temperature of 36.76°C and reached a principal transition peak at 87.01°C, with the minimum heat flow occurring at 85.84°C (– 9.68 mW). The transition exhibited a peak width of 50.93°C and an enthalpy change of – 1495.59 J g⁻¹, indicating substantial molecular rearrangement within the polymer matrix. The maximum heat flow (12.90 mW) occurred at 248.03°C, while the endset temperature was recorded at 244.20°C. The sequence of thermal events is summarised in Table 2B. Following initial stabilisation at 35.01°C, the material exhibited a glass-transition onset at 36.76°C, followed by the principal glass-transition peak at 87.01°C. Structural relaxation occurred at 106.54°C, after which a thermally stable region extended to approximately 154.45°C. A secondary thermal event was observed at 202.24°C before decomposition commenced at approximately 234.54°C, culminating in the maximum thermal response at 248.03°C. Overall, the DSC profile (Table 2C) demonstrated that the material possesses a typical amorphous thermal behaviour characterised by a single dominant glass-transition event without a distinct melting peak. The polymer remained thermally stable up to approximately 230°C before the onset of thermal degradation, indicating good thermal resistance under conventional food-contact conditions.

Table 2

A. Thermal parameters obtained from DSC analysis of polystyrene food packaging material.

Parameter	Value	Unit
Sample Mass	5.60	mg
Heating Rate	10.00	°C min ⁻¹
Temperature Range Investigated	35.01–250.55	°C
Onset Temperature (Thermal Transition)	36.76	°C
Peak Temperature (Glass Transition Region)	87.01	°C
Extrapolated Peak Temperature	165.72	°C
Endset Temperature	244.20	°C
Peak Width	50.93	°C
Peak Height	12.57	mW
Peak Maximum Value	12.90	mW
Normalized Peak Value	2.30	W g ⁻¹
Integral Area	–8375.30	mJ
Specific Enthalpy Change	–1495.59	J g ⁻¹
Minimum Heat Flow	–9.68	mW
Temperature at Minimum Heat Flow	85.84	°C
Maximum Heat Flow	12.90	mW
Temperature at Maximum Heat Flow	248.03	°C

Table 2

B. Major thermal transitions and heat-flow events identified in the DSC thermogram of polystyrene food packaging material.

Thermal Event	Temperature (°C)	Heat Flow (mW)	Interpretation
Initial thermal stabilization	35.01	0.56	Beginning of thermal scan
Glass transition onset (T _g)	36.76	—	Beginning of polymer chain mobility
Endothermic minimum	85.84	−9.68	Maximum heat absorption during glass transition
Glass transition peak	87.01	−9.47	Characteristic T _g of polystyrene
Recovery region	106.54	−3.47	Structural relaxation of polymer chains
Thermal equilibrium region	154.45	0.03	Stable polymer phase
Secondary thermal transition	202.24	0.40	Increased molecular motion
Decomposition onset	234.54	1.82	Beginning of thermal degradation
Endset temperature	244.20	—	Completion of major thermal event
Maximum thermal response	248.03	12.90	Peak decomposition process

Table 2

C. Interpretation of DSC-derived thermal properties showing the characteristic amorphous nature, glass transition behaviour, and thermal stability of the polystyrene packaging material.

Thermal Property	Observation	Significance
Glass transition temperature (T _g)	87.01°C	Typical of amorphous polystyrene
Absence of melting peak	No distinct melting transition observed	Confirms amorphous polymer structure
Thermal stability	Stable up to approximately 230°C	Suitable for conventional food-contact applications
Decomposition onset	234.54°C	Beginning of polymer degradation
Peak decomposition temperature	248.03°C	Maximum thermal decomposition activity
Enthalpy change	-1495.59 J g ⁻¹	Significant energy absorbed during thermal transition
Thermal behaviour	Single dominant thermal event	Characteristic of polystyrene materials
Polymer structure	Predominantly amorphous	Consistent with food-grade expanded polystyrene

Fourier Transform Infrared (FTIR) Characterization

The FTIR spectrum of the polystyrene food packaging material exhibited characteristic absorption bands corresponding to the functional groups expected for a styrene-based polymer (Table 3A). A broad absorption band was observed at 3380.59 cm⁻¹, attributable to O–H stretching, while prominent bands at 2924.03 and 2851.44 cm⁻¹ corresponded to asymmetric and symmetric aliphatic C–H stretching vibrations, respectively. Aromatic C = C stretching was identified at 1636.93 cm⁻¹, with additional aromatic skeletal vibrations occurring at 1491.43 cm⁻¹. The polymer backbone was further represented by CH₂ deformation at 1453.35 cm⁻¹. Within the fingerprint region, strong absorptions at 1098.86 and 1028.37 cm⁻¹, together with the characteristic aromatic C–H out-of-plane bending vibrations at 749.97 and 696.99 cm⁻¹, confirmed the presence of monosubstituted benzene rings. Additional aromatic ring deformation bands were observed at 619.26 and 541.58 cm⁻¹. Grouping of the absorption bands (Table 3B) showed that the spectrum comprised hydroxyl stretching (3380.59 cm⁻¹), aliphatic C–H stretching (2924.03–2851.44 cm⁻¹), aromatic C = C stretching (1636.93 cm⁻¹), aromatic ring and CH₂ deformation (1491.43–1453.35 cm⁻¹), aromatic C–H in-plane vibrations (1098.86–1028.37 cm⁻¹), and the diagnostic aromatic C–H out-of-plane vibrations at 749.97 and 696.99 cm⁻¹. These absorption bands collectively represent the characteristic spectral profile of polystyrene. Overall, the FTIR analysis (Table 3C) confirmed the coexistence of aromatic and aliphatic hydrocarbon structures typical of polystyrene. The strong absorptions associated with monosubstituted benzene rings, together with the aliphatic C–H stretching bands, verified the styrene-derived polymer backbone, while the weak O–H band

suggested only minor surface-associated moisture. The spectral profile therefore confirmed the chemical identity of the packaging material as polystyrene.

Table 3
A. FTIR spectral peak assignments of polystyrene packaging material.

Peak Position (cm ⁻¹)	Peak Intensity	Functional Group Assignment	Vibrational Mode	Interpretation
3380.59	-0.004	O-H stretching	Hydroxyl stretching	Adsorbed moisture or trace hydroxyl-containing compounds
2924.03	0.471	Aliphatic C-H	Asymmetric stretching	Methylene/methyl groups in polymer backbone
2851.44	0.777	Aliphatic C-H	Symmetric stretching	Saturated hydrocarbon chains
1636.93	0.229	C = C aromatic	Aromatic ring stretching	Characteristic benzene ring vibration of polystyrene
1491.43	0.506	Aromatic C = C	Ring skeletal vibration	Phenyl group characteristic of styrene polymers
1453.35	0.650	CH ₂ bending	Deformation vibration	Polymer backbone methylene groups
1098.86	0.746	C-C/C-H aromatic	In-plane vibration	Aromatic ring-associated vibration
1028.37	1.598	Aromatic C-H	In-plane bending	Strong styrene aromatic ring signal
749.97	0.952	Aromatic C-H	Out-of-plane bending	Monosubstituted benzene ring characteristic of polystyrene
696.99	0.626	Aromatic C-H	Out-of-plane bending	Diagnostic peak of polystyrene phenyl ring
619.26	0.613	Aromatic ring deformation	Skeletal vibration	Phenyl ring deformation
541.58	0.591	Aromatic ring deformation	Skeletal vibration	Low-frequency aromatic vibration

Table 3

B. Major functional groups identified in the FTIR spectrum of polystyrene packaging material.

Wavenumber Range (cm ⁻¹)	Observed Peak (cm ⁻¹)	Functional Group	Significance
3600–3200	3380.59	O–H stretching[17]	Surface moisture adsorption
3000–2800	2924.03, 2851.44	Aliphatic C–H stretching[17]	Hydrocarbon polymer backbone
1700–1600	1636.93	Aromatic C = C stretching[18]	Presence of styrene aromatic rings
1500–1400	1491.43, 1453.35	Aromatic ring and CH ₂ bending[18]	Polymer chain structure
1200–1000	1098.86, 1028.37	Aromatic C–H in-plane vibration[19]	Styrene monomer unit
800–650	749.97, 696.99	Aromatic C–H out-of-plane bending[18]	Monosubstituted benzene ring, characteristic of polystyrene
650–500	619.26, 541.58	Ring deformation vibrations[19]	Aromatic skeletal structure

Table 3

C. Interpretation of FTIR findings confirming the characteristic chemical structure of polystyrene packaging material.

Observation	Evidence	Interpretation
Presence of aromatic rings	Peaks at 1636.93, 1491.43, 1028.37, 749.97 and 696.99 cm ⁻¹	Confirms styrene-derived aromatic structure
Hydrocarbon polymer backbone	Peaks at 2924.03 and 2851.44 cm ⁻¹	Indicates aliphatic C–H groups in polymer chain
Monosubstituted benzene ring	Strong peaks at 749.97 and 696.99 cm ⁻¹	Diagnostic fingerprint of polystyrene
Surface moisture	Broad band at 3380.59 cm ⁻¹	Adsorbed atmospheric moisture
Polymer identity	Combined aromatic and aliphatic signatures	Confirms the material as polystyrene packaging

Differential Thermal Analysis (DTA)

The DTA thermogram demonstrated a characteristic thermal response of the polystyrene packaging material from ambient temperature to approximately 440°C (Table 4A). The analysis began at 28.6°C with an initial DTA signal of + 0.220% min⁻¹. A distinct glass-transition region occurred between 58 and 62°C, with a peak transition temperature of approximately 58.7°C. This was followed by an endothermic region extending from 60 to 150°C, during which the minimum DTA value (– 0.238% min⁻¹) was recorded. The material subsequently exhibited a thermally stable region between 150 and 250°C before the onset

of thermal decomposition at approximately 300°C. The principal degradation stage occurred between 300 and 440°C, reaching a maximum degradation rate of $-4.87\% \text{ min}^{-1}$ near 440°C. The major thermal events identified during DTA analysis are summarised in Table 4B. Initial moisture and volatile release occurred between 28 and 58°C, followed by the glass transition (58–62°C) and polymer relaxation between 62 and 150°C. A broad thermal stability plateau extended from 150 to 300°C before primary decomposition commenced between 300 and 380°C. The highest degradation rate occurred within the 380–440°C interval, after which residual degradation continued beyond 440°C. Derived thermal stability indices (Table 4C) indicated a glass-transition temperature of approximately 59°C, with both the thermal stability limit and decomposition onset occurring near 300°C. Maximum degradation occurred at approximately 440°C with a degradation rate of $-4.87\% \text{ min}^{-1}$. The polymer exhibited a single dominant decomposition stage and high thermal resistance, remaining stable under temperatures typically encountered during food packaging and storage.

Table 4

A. Differential thermal analysis characteristics of polystyrene food packaging material showing thermal transitions and decomposition behaviour.

Parameter	Value	Interpretation
Initial analysis temperature	28.6°C	Start of thermal scan
Initial DTA signal	+ 0.220% min ⁻¹	Initial thermal response
Glass transition region (T _g)	58–62°C	Transition from glassy to rubbery state indicated by zero-crossing of the DTA signal
Peak transition temperature	~ 58.7°C	Thermal relaxation point
Endothermic region	60–150°C	Energy absorption associated with polymer chain mobility
Minimum DTA value in first transition	-0.238% min ⁻¹	Maximum endothermic response around 150°C
Stable thermal region	150–250°C	No major thermal event observed
Onset of thermal decomposition	~ 300°C	Beginning of polymer degradation
Main degradation region	300–440°C	Rapid depolymerization and styrene evolution
Maximum degradation rate	-4.87% min ⁻¹	Peak decomposition rate near 440°C
Final temperature analysed	~ 440°C	End of thermal scan
Thermal behaviour	Single major degradation stage	Characteristic of polystyrene polymers

Table 4

B. Major thermal events observed during DTA analysis of polystyrene food packaging material.

Thermal Event	Temperature Range (°C)	DTA Response (% min ⁻¹)	Interpretation
Moisture/volatile release	28–58	+ 0.220 to 0.000	Loss of adsorbed moisture and residual volatiles
Glass transition (T _g)	58–62	0.000 to – 0.010	Transition from rigid to rubbery polymer state
Polymer relaxation	62–150	–0.010 to – 0.238	Increased molecular mobility
Thermal stability plateau	150–300	Approximately constant	No significant thermal degradation
Primary decomposition	300–380	–1.10 to – 3.50	Chain scission and depolymerization
Major degradation peak	380–440	–3.50 to – 4.87	Maximum breakdown of polymer backbone
Residual degradation	> 440	Terminal stage	Formation of volatile degradation products

Table 4

C. Derived thermal stability parameters obtained from DTA analysis indicating high thermal stability of the packaging material up to approximately 300°C, followed by rapid thermal degradation characteristic of polystyrene.

Thermal Stability Index	Value
Glass transition temperature (T _g)	~ 59°C
Thermal stability limit	~ 300°C
Decomposition onset temperature (Tonset)	~ 300°C
Temperature at maximum degradation rate (T _{max})	~ 440°C
Maximum degradation rate	–4.87% min ⁻¹
Major degradation interval	300–440°C
Number of decomposition stages	One dominant stage
Thermal resistance classification	High
Suitability for food-contact applications	Stable under normal food-processing temperatures
Polymer degradation mechanism	Depolymerization with styrene monomer evolution

Thermogravimetric Analysis (TGA)

The thermogravimetric profile of the polystyrene food packaging material demonstrated high thermal stability over a broad temperature range (Table 5A). The sample exhibited an initial weight of 100.05% at 28.6°C, with a slight increase to 100.22% at 56.2°C attributable to instrumental stabilisation. Weight retention remained high throughout the early stages of heating, with 99.93%, 98.81% and 97.67% of the original mass retained at 100, 150 and 200°C, respectively. At approximately 250°C, the material retained about 96.50% of its initial weight, indicating the onset of gradual degradation. More pronounced mass loss occurred above 300°C, where weight retention decreased to 95.37%, followed by rapid degradation between 300 and 350°C, leaving approximately 82.50% residual mass at 350°C. The principal decomposition region extended between 300 and 400°C. The degradation behaviour was resolved into five distinct thermal stages (Table 5B). Stage I (28–100°C) was characterised by minimal weight loss associated with moisture and residual volatile removal. Stage II (100–200°C) involved slight mass reduction due to the release of low-molecular-weight compounds. Stage III (200–300°C) marked the onset of polymer decomposition, while Stage IV (300–350°C) represented the principal degradation phase with rapid depolymerisation and substantial weight loss. Stage V (> 350°C) consisted of progressive degradation of the remaining polymer matrix. Thermal stability indices derived from the TGA profile (Table 5C) showed an initial decomposition temperature (IDT) of approximately 250°C, with temperatures corresponding to 5% and 10% weight loss (T_5 and T_{10}) of approximately 310 and 332°C, respectively. The polymer exhibited a single dominant decomposition stage, low char formation and high thermal stability, retaining over 95% of its original mass up to 300°C before rapid degradation occurred.

Table 5

A. Thermogravimetric characteristics of polystyrene food packaging material showing thermal stability and degradation behaviour during controlled heating.

Thermal Parameter	Value	Observation
Initial Temperature (Ti)	28.6°C	Beginning of analysis
Initial Weight	100.05%	Baseline sample weight
Temperature at Maximum Weight	56.2°C	Slight increase due to instrumental stabilization
Maximum Weight	100.22%	Highest recorded mass
Weight at 100°C	99.93%	Minimal mass loss
Weight at 150°C	98.81%	High thermal stability maintained
Weight at 200°C	97.67%	Minor volatilization stage
Weight at 250°C*	~ 96.50%	Beginning of gradual degradation
Weight at 300°C	95.37%	Onset of significant decomposition
Weight at 325°C*	~ 91.30%	Accelerated polymer degradation
Weight at 350°C*	~ 82.50%	Major decomposition stage
Temperature of Main Decomposition	300–400°C	Principal weight-loss region
Total Weight Loss at 200°C	2.38%	Low-temperature mass loss
Total Weight Loss at 300°C	4.68%	Early decomposition
Residual Weight at 350°C*	~ 82.50%	Remaining polymer fraction
Overall Thermal Stability Range	28–300°C	Stable under food-contact conditions

Table 5

B. Degradation stages identified from the thermogravimetric profile of the polystyrene food packaging material.

Stage	Temperature Range (°C)	Weight Change (%)	Thermal Event	Interpretation
I	28–100	100.05–99.93	Moisture/volatile loss	Removal of adsorbed moisture and residual volatiles
II	100–200	99.93–97.67	Initial degradation	Loss of low-molecular-weight compounds
III	200–300	97.67–95.37	Onset of decomposition	Polymer chain scission begins
IV	300–350	95.37–82.50	Major degradation	Rapid depolymerization and styrene evolution
V	> 350	Progressive decline	Advanced degradation	Breakdown of polymer matrix and aromatic fragments

Table 5

C. Derived thermal stability indices obtained from TGA analysis of the polystyrene food packaging material.

Parameter	Value
Initial decomposition temperature (IDT)	~ 250°C
Temperature at 5% weight loss (T_5)	~ 310°C
Temperature at 10% weight loss (T_{10})	~ 332°C
Main degradation range	300–400°C
Maximum stability region	28–250°C
Weight retained at 100°C	99.93%
Weight retained at 200°C	97.67%
Weight retained at 300°C	95.37%
Thermal behaviour	Single-stage dominant decomposition
Char-forming tendency	Low
Thermal stability classification	High

3.6 Styrene Migration from Polystyrene Packaging into Food Simulants

Styrene migration was detected in all food simulants at 25, 40 and 70°C, with retention times remaining highly consistent (5.41–5.43 min), confirming reliable chromatographic identification of the analyte (Tables 6A–6C).

At **70°C** (Table 6A), styrene migration was highest in 10% ethanol ($128.6 \pm 5.4 \mu\text{g/L}$; $0.129 \pm 0.005 \text{ mg/L}$), followed by vegetable oil ($116.7 \pm 5.3 \mu\text{g/L}$), 3% acetic acid ($112.8 \pm 5.1 \mu\text{g/L}$) and distilled water ($99.6 \pm 4.8 \mu\text{g/L}$). Correspondingly, peak areas ranged from 4529 to 5842 mAU·s, with ethanol producing the largest chromatographic response.

At **40°C** (Table 6B), migration levels were markedly lower than those observed at 70°C. Distilled water recorded the highest styrene concentration ($68.9 \pm 3.2 \mu\text{g/L}$), followed by 3% acetic acid ($62.3 \pm 3.0 \mu\text{g/L}$), vegetable oil ($58.1 \pm 2.9 \mu\text{g/L}$) and 10% ethanol ($56.7 \pm 2.8 \mu\text{g/L}$). Peak areas ranged from 3268 to 3704 mAU·s.

At **25°C** (Table 6C), corresponding to ambient storage conditions, styrene concentrations were lowest across all simulants. Distilled water and 10% ethanol each recorded $18.3 \pm 1.2 \mu\text{g/L}$, while vegetable oil and 3% acetic acid contained 16.8 ± 1.1 and $15.6 \pm 1.0 \mu\text{g/L}$, respectively. Peak areas varied between 1757 and 2540 mAU·s.

Comparison of the three temperature conditions demonstrated a clear temperature-dependent increase in styrene migration (Figure/Table 6). Across all simulants, styrene concentrations increased progressively from 25 to 40 and 70°C. Distilled water increased from 18.3 to 68.9 and 99.6 $\mu\text{g/L}$, 10% ethanol from 18.3 to 56.7 and 128.6 $\mu\text{g/L}$, 3% acetic acid from 15.6 to 62.3 and 112.8 $\mu\text{g/L}$, and vegetable oil from 16.8 to 58.1 and 116.7 $\mu\text{g/L}$. Overall, elevated temperature consistently enhanced styrene migration irrespective of the food simulant, although the extent of migration varied among simulants.

Table 6
A. Styrene Concentrations in Different Food Simulants at 70°C Polystyrene Food Packaging Leachability Study (HPLC Analysis)

Simulant	Styrene Retention Time (min)	Peak Area (mAU·s)	Styrene Concentration ($\mu\text{g/L}$)	Concentration (mg/L)
Distilled Water	5.42	4529	99.6 ± 4.8	0.100 ± 0.005
10% Ethanol	5.43	5842	128.6 ± 5.4	0.129 ± 0.005
3% Acetic Acid	5.42	5124	112.8 ± 5.1	0.113 ± 0.005
Vegetable Oil	5.42	5301	116.7 ± 5.3	0.117 ± 0.005

Table 6

B. Styrene Concentrations in Different Food Simulants at 40°C **Migration of Styrene from Polystyrene Food Packaging Determined by HPLC**

Simulant	Retention Time (min)	Peak Area (mAU·s)	Styrene Concentration (µg/L)	Concentration (mg/L)
Distilled Water	5.41	3704	68.9 ± 3.2	0.0689 ± 0.0032
10% Ethanol	5.42	3268	56.7 ± 2.8	0.0567 ± 0.0028
3% Acetic Acid	5.41	3486	62.3 ± 3.0	0.0623 ± 0.0030
Vegetable Oil	5.41	3268	58.1 ± 2.9	0.0581 ± 0.0029

Table 6

C. Styrene Concentrations in Different Food Simulants at 25°C **Migration of Styrene from Polystyrene Food Packaging Determined by HPLC**

Simulant	Retention Time (min)	Peak Area (mAU·s)	Styrene Concentration (µg/L)	Concentration (mg/L)
Distilled Water	5.41	2540	18.3 ± 1.2	0.0183 ± 0.0012
10% Ethanol	5.43	1757	18.3 ± 1.2	0.0183 ± 0.0012
3% Acetic Acid	5.41	2146	15.6 ± 1.0	0.0156 ± 0.0010
Vegetable Oil	5.41	1757	16.8 ± 1.1	0.0168 ± 0.0011

Discussion

The elemental profile (Table 1A-C) obtained from the SEM–EDS analysis is characteristic of a hydrocarbon-based polymer and provides important insights into the compositional integrity of the polystyrene food packaging material. The dominance of carbon is consistent with the molecular architecture of polystyrene, which is synthesized through the polymerization of styrene monomers containing aromatic benzene rings attached to carbon-rich aliphatic chains. The overwhelming prevalence of carbon therefore confirms that the packaging material retained its polymeric identity and had not undergone substantial compositional alteration through degradation, contamination, or excessive incorporation of inorganic fillers. Carbon constitutes the major structural framework responsible for the material's lightweight nature, hydrophobicity, thermal insulation properties, and mechanical stability, consistent with commercial polystyrene products[20].

The presence of nitrogen suggests that the packaging material is not composed solely of the base polymer but contains additional constituents introduced during manufacturing or subsequent handling.

Since nitrogen is not a structural component of polystyrene, its occurrence may be linked to nitrogen-containing processing aids, stabilizers, foaming agents, colourants, or residual monomeric compounds used during production. Food-contact plastics are frequently formulated with numerous proprietary additives designed to enhance performance characteristics such as flexibility, durability, thermal resistance, and shelf life. Nitrogen may also originate from surface adsorption of environmental compounds during storage and distribution. Similar observations have been reported by [21], who identified non-structural elements in commercial packaging materials and attributed them to additive incorporation and environmental interactions. The finding highlights the chemical complexity of food packaging polymers and underscores the importance of evaluating not only the polymer itself but also associated additives that may contribute to migration phenomena.

The occurrence of silicon, calcium, magnesium, and aluminium is indicative of mineral-based additives commonly employed in polymer manufacturing. These elements are frequently associated with fillers, anti-caking agents, reinforcing compounds, and stabilizers that improve physical performance while reducing production costs. Silicon-containing materials, particularly silica derivatives, are often incorporated to enhance thermal stability and mechanical strength, whereas calcium-based compounds can improve rigidity and dimensional stability. Their detection supports previous reports that commercial packaging polymers rarely exist as chemically pure materials but instead represent complex formulations engineered to achieve specific functional properties [22], [23].

The detection of iron, manganese, and vanadium likely reflects residual traces arising from catalyst systems, manufacturing equipment, or industrial processing operations. Metallic residues have been reported in several polymer products owing to the widespread use of metal-containing catalysts during polymer synthesis and the potential for contamination from processing machinery. Previous report noted that trace metals are frequently encountered in plastic materials even when they are not intentionally added as functional ingredients [24]. Their presence in low concentrations therefore appears to be consistent with normal industrial production processes rather than deliberate formulation components.

The identification of these trace metals also has toxicological relevance because metallic constituents may influence polymer degradation pathways and migration behaviour during prolonged storage or exposure to elevated temperatures. Studies have demonstrated that certain transition metals can catalyse oxidative degradation reactions within polymer matrices, potentially increasing the formation of low-molecular-weight degradation products that may subsequently migrate into food systems [25]. Although the concentrations detected in the present study are relatively low, their presence may contribute indirectly to chemical transformations occurring during repeated heating or long-term usage of the packaging material.

The absence of chlorine is particularly significant because chlorine is commonly associated with polyvinyl chloride and chlorinated additives. Its non-detection provides additional confirmation that the packaging material was composed predominantly of polystyrene and was not contaminated by

substantial quantities of chlorinated polymers. This observation is important from an environmental and toxicological standpoint because chlorinated plastic additives have been implicated in the formation of hazardous compounds during thermal decomposition and waste incineration. Similar findings were reported by [26], who noted that polymers lacking chlorine generally present lower risks of generating chlorinated toxicants during degradation processes.

Likewise, the absence of phosphorus and sulfur suggests limited reliance on phosphorus-based flame retardants and sulfur-containing stabilizers. This differs from some commercial plastic formulations in which these elements are incorporated to improve fire resistance and processing stability [27]. The discrepancy may reflect differences in manufacturing objectives, regulatory requirements, or intended product applications. Food packaging materials often prioritize chemical inertness and consumer safety over flame-retardant functionality, which may explain the absence of these additives in the present material.

The non-detection of titanium also contrasts with reports describing the widespread use of titanium dioxide as a whitening pigment in food-contact plastics. For example, [28] identified titanium-containing pigments in numerous consumer packaging products. The absence of titanium in the present study may indicate either a transparent or lightly pigmented formulation, or the use of alternative colouring agents. Such variability highlights the diversity of manufacturing practices within the packaging industry and demonstrates that additive composition is strongly influenced by product design requirements.

Collectively, the elemental composition suggests that the packaging material was formulated with relatively few inorganic additives and remained predominantly composed of the parent polymer matrix. This observation aligns with the goal of designing food-grade polystyrene products to maintain chemical simplicity while achieving the mechanical and thermal characteristics necessary for food containment. The limited abundance of metallic and mineral constituents may also be advantageous from a food safety perspective because it reduces the likelihood of significant inorganic contaminant migration.

From a toxicological perspective, the findings imply that any potential chemical release from the packaging material is more likely to originate from organic constituents, including residual styrene monomers, oligomers, degradation products, and associated organic additives, rather than from inorganic elements. This interpretation is consistent with previous migration studies that have identified styrene and related aromatic compounds as the principal contaminants released from polystyrene food packaging under thermal and storage conditions [29]. Consequently, the elemental profile provides a foundational understanding of the material composition and establishes a mechanistic basis for subsequent investigations into styrene migration, thermal degradation, and human exposure risks associated with polystyrene food-contact materials.

The classification of the detected elements according to their relative abundance provides a clearer understanding of the compositional hierarchy of the polystyrene food packaging material and offers insight into the functional roles of the various constituents within the polymer matrix. Such categorization is important because it distinguishes between elements that define the fundamental

structure of the material and those that are present as additives, processing residues, or incidental contaminants. The elemental distribution observed in the present study reflects the complex nature of modern food-contact polymers, which are rarely composed exclusively of the parent polymer but instead comprise a combination of structural constituents and auxiliary compounds introduced during manufacture.

The designation of carbon as the sole major element is consistent with the chemical structure of polystyrene and confirms that the packaging material is fundamentally an organic polymer. Carbon serves as the backbone of the polymeric framework and is directly responsible for many of the characteristic properties of polystyrene, including its low density, hydrophobicity, mechanical rigidity, and thermal insulation capacity. Similar classifications have been reported in studies examining commercial polystyrene products, where carbon overwhelmingly dominates the elemental profile owing to the aromatic and aliphatic carbon arrangements present within styrene-derived macromolecules [30], [31]. The predominance of carbon therefore reinforces the structural integrity of the material and indicates that the packaging retained the essential characteristics expected of food-grade polystyrene.

Nitrogen was identified as a secondary constituent, suggesting a role that is important but not structurally defining. The occurrence of nitrogen in polymeric materials has frequently been associated with functional additives incorporated to modify processing behaviour, improve product performance, or enhance stability during storage and use. Nitrogen-containing compounds are commonly utilized as blowing agents, stabilizers, antioxidants, colourants, and processing aids in the plastics industry [32]. Consequently, the classification of nitrogen as a secondary element supports the notion that the packaging material underwent formulation modifications beyond the base polymer composition.

Previous investigations have similarly identified nitrogen as a non-structural but functionally relevant component of food packaging plastics. Likewise, [33] demonstrated that food-contact materials contain numerous chemical additives capable of altering migration behaviour, surface chemistry, and long-term stability. The present findings therefore suggest that nitrogen-containing constituents may contribute to the physicochemical behaviour of the packaging material, particularly under conditions of heating, storage, or prolonged food contact.

The classification of iron, silicon, calcium, manganese, aluminium, magnesium, and vanadium as trace elements is characteristic of commercial polymer products and reflects the multifaceted nature of industrial manufacturing processes. Although these elements do not contribute significantly to the overall composition of the material, their presence provides valuable information regarding raw material sources, production technologies, catalyst systems, and additive formulations. Trace inorganic constituents often function as stabilizers, fillers, pigments, reinforcing agents, nucleating compounds, or processing aids designed to improve specific material properties [34].

The occurrence of silicon and calcium is particularly consistent with their widespread application as mineral additives in polymer manufacturing. Silica-based compounds are commonly employed to improve mechanical strength, abrasion resistance, and thermal stability, while calcium-containing

materials are frequently used as cost-effective fillers that enhance rigidity and dimensional stability [35]. Similar observations were reported by [36], who noted that mineral additives are routinely incorporated into plastic packaging materials to optimize performance characteristics without substantially altering the overall polymer composition.

Aluminium and magnesium are likewise frequently encountered in commercial plastics as constituents of stabilizing systems and processing additives. Their presence may reflect the use of mineral-derived additives or residues introduced during compounding and fabrication processes. According to research[37], aluminium- and magnesium-based compounds are widely employed to improve heat resistance, reduce degradation during processing, and enhance long-term product durability. The detection of these elements therefore supports the view that the packaging material was engineered to achieve specific functional properties rather than being composed solely of the base polymer.

The presence of iron, manganese, and vanadium may be linked to industrial processing operations, catalyst residues, or wear of manufacturing equipment. Several studies have demonstrated [24], [38] that trace metallic elements can become incorporated into polymer matrices during polymerization, extrusion, moulding, or packaging production. These metals may also originate from environmental contamination during storage and transportation. Similar findings were reported by[39], which identified a broad spectrum of metallic impurities in consumer plastics and emphasized that such constituents often reflect production history rather than intentional formulation.

An important implication of the trace element distribution is that polymeric food packaging materials should not be viewed as chemically inert systems. Instead, they represent dynamic and chemically heterogeneous matrices containing a variety of intentionally and unintentionally introduced substances. This perspective is supported by [40], who argued that plastic packaging materials comprise complex mixtures of polymers, additives, degradation products, and contaminants that collectively determine material behaviour and potential migration risks. The trace constituents identified in the present study may therefore influence not only the physical properties of the packaging but also its interactions with food matrices during storage and heating.

The observed elemental hierarchy further suggests that the physicochemical properties of the packaging material arise from interactions between the dominant polymer matrix and the minor additive components. Previous studies have shown that even low concentrations of inorganic additives can substantially affect thermal stability, mechanical strength, oxidative resistance, and chemical migration patterns [34], [41]. Consequently, although the trace elements constitute only a small fraction of the overall composition, they may exert disproportionate effects on material performance and degradation behaviour.

The findings of the present study are consistent with investigations reporting chemically complex compositions in commercial food packaging materials. However, they contrast with studies involving laboratory-grade or highly purified polystyrene standards, which often exhibit substantially lower levels of trace inorganic constituents due to stricter manufacturing controls and the absence of performance-

enhancing additives [42]. This distinction highlights the importance of evaluating commercial packaging materials in their actual consumer form rather than relying exclusively on idealized polymer standards when assessing environmental and toxicological implications.

From a food safety perspective, the identification of secondary and trace constituents underscores the need to consider additive-related migration alongside the migration of residual styrene monomers and oligomers. Numerous investigations have demonstrated that additives may contribute significantly to the chemical burden released from food-contact materials, particularly under elevated temperatures and prolonged storage conditions [8]. The elemental classification observed in the present study therefore provides an important foundation for understanding subsequent migration behaviour and assessing potential consumer exposure associated with the use of polystyrene food packaging.

SEM–EDS Characterisation

The SEM–EDS analysis confirmed that the investigated food packaging material possesses the elemental characteristics expected of commercial polystyrene while also revealing the compositional complexity typical of engineered food-contact polymers. Carbon overwhelmingly dominated the elemental profile, consistent with the aromatic hydrocarbon backbone formed through polymerisation of styrene monomers. This predominance confirms that the material largely retained its intrinsic polymeric identity without evidence of substantial inorganic dilution or extensive degradation. The high carbon content is directly associated with the physicochemical properties that make polystyrene attractive for food packaging, including low density, rigidity, hydrophobicity and thermal insulation, all of which originate from its aromatic molecular architecture [31], [43]

Although carbon defines the structural framework of the polymer, the detection of nitrogen demonstrates that the packaging material is not chemically homogeneous. Because nitrogen is absent from the repeating styrene unit, its presence most likely reflects the incorporation of nitrogen-containing additives, processing aids, foaming agents, stabilisers, pigments or residual manufacturing constituents. Food-contact plastics are rarely composed of pure polymers; instead, they represent carefully engineered formulations designed to optimise mechanical performance, processability, durability and shelf stability. Surface adsorption of environmental contaminants during manufacture, storage or distribution may also contribute to the observed nitrogen signal. Similar observations have been reported for commercial polymeric packaging materials, where non-structural elements were attributed to additive incorporation and environmental interactions [44]. Consequently, the elemental profile indicates that potential migration behaviour should be evaluated not only in terms of the base polymer but also with respect to associated additives that may influence chemical release.

The occurrence of silicon, calcium, magnesium and aluminium further supports the presence of mineral-based additives commonly employed during polymer manufacture. Silica derivatives are widely used to improve thermal resistance, dimensional stability and mechanical strength, whereas calcium-containing fillers enhance rigidity and reduce production costs. Magnesium- and aluminium-containing compounds

may similarly function as reinforcing agents or processing stabilisers. Their occurrence reinforces the concept that commercial polystyrene packaging is a multifunctional composite material rather than a chemically pure polymer, consistent with previous descriptions of industrial food-contact plastics[45] .

Trace concentrations of iron, manganese and vanadium most plausibly originate from catalyst residues, processing equipment or manufacturing operations. Metallic impurities are frequently reported in polymeric materials despite not being intentionally incorporated as functional ingredients because transition-metal catalysts are widely used during polymer synthesis and trace contamination may occur throughout production. Similar findings have been documented in commercial plastic products, where residual metals remain detectable at low concentrations following polymer processing [24]. Although the detected levels are unlikely to influence the bulk physicochemical properties of the material, they provide valuable evidence of the industrial processing history of the polymer and may contribute to oxidative reactions during prolonged environmental ageing.

FTIR Characterisation

The FTIR spectrum confirmed the molecular identity of the packaging material as polystyrene by revealing the characteristic vibrational signatures of aromatic hydrocarbon polymers[18], [46] The simultaneous presence of aromatic C = C stretching, aliphatic C–H stretching and monosubstituted benzene ring vibrations demonstrates that the polymeric network remained chemically intact throughout manufacture and analysis. These spectral characteristics are consistent with the molecular architecture expected for commercial polystyrene and verify that the material retained its fundamental chemical structure without evidence of substantial oxidative degradation or chemical transformation.

The broad absorption assigned to O–H stretching suggests the presence of adsorbed moisture or hydroxyl-containing surface species rather than intrinsic structural hydroxyl groups, since pristine polystyrene does not contain oxygen-bearing functional groups[47]. Such bands are commonly attributed to atmospheric moisture adsorption or interactions between the polymer surface and environmental contaminants. Their relatively weak intensity indicates that these interactions remain largely superficial and do not alter the underlying polymer chemistry.

Strong absorptions corresponding to aliphatic C–H stretching confirm the saturated hydrocarbon backbone linking successive styrene repeat units, whereas the aromatic C = C vibration reflects the persistence of pendant benzene rings that distinguish polystyrene from other commodity plastics. The characteristic bands associated with aromatic ring deformation and out-of-plane C–H bending further verify the presence of monosubstituted benzene structures, providing additional confirmation of the polymer's molecular identity. Similar FTIR fingerprints have consistently been reported for commercial polystyrene packaging materials and recycled polystyrene products [47], [48]

The preservation of these characteristic functional groups has important implications for the material's thermal and migration behaviour. Aromatic benzene rings impart rigidity through restricted rotational mobility and enhanced intermolecular interactions, thereby contributing to the high thermal resistance

and structural stability of polystyrene. At the same time, these aromatic domains constitute the molecular origin of styrene, the principal migrant of toxicological concern in food-contact applications[49]. Consequently, the FTIR results not only confirm polymer identity but also establish the molecular basis for understanding the subsequent thermal decomposition profile and the temperature-dependent release of residual styrene observed during migration experiments.

DSC Characterisation

Differential scanning calorimetry demonstrated that the investigated polystyrene packaging possesses a well-defined thermal transition profile characteristic of an amorphous styrene-based polymer[46]. The presence of distinct thermal events, including glass transition, molecular relaxation and progressive thermal transformation, indicates that the material retains a stable polymeric architecture capable of withstanding normal food storage and handling conditions. Rather than exhibiting abrupt structural instability, the DSC thermogram reflects a controlled response to increasing temperature, suggesting that molecular mobility develops gradually before significant thermal degradation occurs.

The initial thermal transition observed near the onset temperature corresponds to increased segmental motion of the polymer chains as thermal energy overcomes intermolecular restrictions within the amorphous matrix[50]. Below this transition, the polymer exists in a rigid glassy state in which chain mobility is severely restricted. As temperature increases, greater molecular flexibility develops, allowing localised rearrangement of the polymer network while maintaining overall structural integrity. Similar behaviour has been widely reported for commercial polystyrene and reflects the characteristic response of amorphous aromatic polymers to thermal stimulation [50].

The principal endothermic transition centred around the major DSC peak represents enhanced molecular relaxation within the polymer matrix rather than chemical decomposition. Because polystyrene lacks crystalline domains[50], this thermal event reflects progressive softening of the amorphous structure through increased rotational freedom of the polymer backbone and pendant phenyl groups. The aromatic rings restrict complete molecular mobility, resulting in a relatively narrow thermal transition that preserves dimensional stability across a broad temperature interval. This behaviour explains why expanded and rigid polystyrene products retain their structural form under moderate thermal conditions despite undergoing increasing molecular motion.

The recovery of thermal equilibrium following the principal transition indicates that the absorbed thermal energy is redistributed efficiently throughout the polymer network without immediate disruption of covalent bonding[51]. This observation suggests that the polymer remains chemically stable after softening and that thermal energy is initially consumed by molecular rearrangement rather than bond scission. Such behaviour is consistent with the known thermal characteristics of polystyrene, in which substantial degradation generally occurs only after extensive chain mobility has already developed [51].

The secondary thermal event observed at higher temperature further illustrates the progressive evolution of the polymer structure during heating. This transition likely reflects continued relaxation of longer

polymer chains together with the onset of molecular processes that precede depolymerisation[52]. Although no extensive decomposition occurs at this stage, the increased molecular mobility may facilitate diffusion of residual low-molecular-weight constituents trapped within the polymer matrix. Consequently, the DSC profile provides an important mechanistic explanation for the temperature-dependent migration behaviour observed in the present study, where elevated temperatures promoted greater styrene release despite the absence of significant polymer degradation.

The delayed onset of thermal decomposition observed at still higher temperatures confirms the inherent thermal resilience of the packaging material. Aromatic polystyrene possesses relatively high bond dissociation energies, particularly within the phenyl-substituted backbone, allowing the material to tolerate considerable thermal exposure before irreversible chemical breakdown begins[53]. The DSC results therefore demonstrate that softening and increased molecular mobility precede polymer degradation by a substantial temperature margin. This distinction is important for food-contact applications because migration of residual styrene can occur well before temperatures capable of degrading the polymer are reached[49].

DTA Characterisation

The differential thermal analysis further substantiates the thermal stability of the polystyrene packaging by demonstrating a characteristic sequence of thermal transitions associated with amorphous polymer behaviour. The observed glass transition temperature confirms the conversion of the polymer from a rigid glassy state to a more flexible rubbery state as thermal energy increases. This transition represents a physical transformation rather than chemical degradation and is governed primarily by increased segmental mobility within the amorphous polymer network.

The measured glass transition temperature agrees well with values reported for commercial polystyrene, confirming that the material possesses the thermal characteristics expected of food-grade styrene-based packaging [54]. Below this temperature, restricted chain mobility contributes to the dimensional stability and mechanical rigidity required for packaging applications[50]. Above the transition, however, increasing chain flexibility enhances free volume within the polymer matrix, facilitating diffusion of residual monomeric species[50]. Consequently, the DTA results provide an important mechanistic explanation for the progressive increase in styrene migration observed as experimental temperature increased.

The absence of major exothermic or endothermic decomposition events immediately after the glass transition indicates that the polymer remains chemically stable despite increased molecular mobility. This distinction highlights that thermal softening and thermal degradation are independent processes. While the polymer becomes more flexible above the glass transition, its molecular backbone remains largely intact until considerably higher temperatures are reached. Such behaviour is characteristic of amorphous aromatic polymers, where enhanced chain mobility precedes bond cleavage by a substantial thermal interval[55].

The onset of decomposition at approximately 300°C demonstrates the high thermal resistance imparted by the aromatic styrene framework[51]. Cleavage of carbon–carbon bonds within the polymer backbone requires substantially greater thermal energy than that needed for molecular relaxation, explaining the wide separation between glass transition and decomposition temperatures. This thermal stability reflects the contribution of phenyl groups, which increase chain stiffness and retard thermal degradation by stabilising the polymer structure against random bond rupture.

The maximum decomposition rate occurring near 440°C is characteristic of rapid depolymerisation once thermal degradation is initiated. At this stage, chain scission proceeds extensively, producing volatile degradation products, predominantly styrene monomer together with other aromatic fragments generated through unzipping reactions. Similar degradation mechanisms have been extensively described for polystyrene and reflect the inherent tendency of styrene-based polymers to depolymerise once sufficient activation energy is attained[56]. The sharp decomposition profile therefore indicates that the material remains highly stable until a critical thermal threshold is exceeded, after which degradation proceeds rapidly.

From a food-contact perspective, the DTA findings demonstrate that the temperatures investigated for migration studies remain well below those required for thermal decomposition. Consequently, the styrene detected in food simulants is unlikely to originate from degradation of the polymer backbone. Instead, migration is more plausibly explained by diffusion of residual monomer and other low-molecular-weight species through a polymer matrix whose free volume increases progressively with temperature. This distinction is critical because it indicates that migration under realistic use conditions is primarily a diffusion-controlled phenomenon rather than a consequence of thermal decomposition[57].

TGA Characterisation

Thermogravimetric analysis demonstrated that the investigated polystyrene packaging possesses excellent thermal stability over a broad temperature range, with only minimal mass loss occurring during the initial stages of heating. The negligible reduction in sample mass below 100°C indicates that the material contains very low levels of physically adsorbed moisture or volatile contaminants, confirming the hydrophobic nature of polystyrene and the absence of appreciable quantities of residual solvents or other low-boiling constituents. This behaviour is consistent with the non-polar aromatic structure of polystyrene, which exhibits limited affinity for water and retains its structural integrity under normal food storage and moderate heating conditions [58], [59]

The slight mass reduction observed between 100 and 300°C reflects the gradual elimination of trace volatile components and low-molecular-weight species rather than degradation of the polymer backbone. At these temperatures, limited evaporation of residual processing additives, unreacted styrene monomer, or other volatile constituents may occur while the primary polymeric network remains chemically intact. The relatively small magnitude of mass loss during this interval indicates that the material is well polymerised and contains only minor quantities of extractable compounds. This

observation complements the SEM–EDS findings, which demonstrated the presence of additive-derived inorganic constituents, suggesting that commercial food-contact polystyrene is a carefully engineered formulation with minimal volatile impurities[60].

A marked increase in mass loss occurred between 300 and 400°C, identifying this region as the principal thermal degradation stage of the polymer. This behaviour is characteristic of polystyrene, whose degradation proceeds predominantly through random chain scission followed by depolymerisation via an unzipping mechanism that regenerates styrene monomer together with other volatile aromatic products. Once thermal activation exceeds the stability of the polymer backbone, cleavage of carbon–carbon bonds initiates rapid molecular fragmentation, producing the characteristic steep decline in residual mass. Similar degradation profiles have consistently been reported for commercial and laboratory-synthesised polystyrene materials [58], [60]

The delayed onset of substantial weight loss demonstrates the intrinsic thermal resilience imparted by the aromatic phenyl groups attached to the polymer backbone. These aromatic structures increase chain stiffness and stabilise the macromolecular network by restricting rotational freedom and enhancing intermolecular interactions. Consequently, considerable thermal energy is required before irreversible degradation begins. The high values obtained for the initial decomposition temperature (IDT), together with the temperatures corresponding to 5% and 10% mass loss (T_5 and T_{10}), confirm that the investigated packaging material possesses thermal stability comparable with that reported for commercial food-grade polystyrene [61], [62]. These indices further indicate that the polymer is unlikely to undergo structural degradation under normal food storage or conventional food-service conditions.

The close agreement between the DSC, DTA and TGA results provides strong evidence that thermal relaxation and polymer decomposition are distinctly separate processes. Whereas DSC and DTA demonstrated that increasing temperature enhances molecular mobility above the glass transition, TGA confirms that the polymer backbone remains chemically stable until temperatures far exceeding those employed in the migration experiments are reached. This distinction is particularly important because it indicates that thermal exposure within the experimental range does not induce degradation of the polymer itself but instead promotes diffusion of pre-existing low-molecular-weight constituents through an increasingly mobile polymer matrix.

From a food safety perspective, the thermogravimetric behaviour has important implications for interpreting styrene migration. The migration experiments were performed at temperatures substantially below the onset of significant thermal decomposition, indicating that the detected styrene did not arise from degradation of the polymer backbone. Rather, increasing temperature most likely accelerated diffusion of residual styrene entrapped within the polymer matrix by increasing chain mobility and free volume. Consequently, the TGA data support a diffusion-controlled mechanism of migration rather than one driven by thermal breakdown of the polymer.

The TGA results also reinforce the suitability of polystyrene for applications requiring moderate thermal resistance. Although the material remains structurally stable throughout normal service temperatures,

the progressive increase in molecular mobility demonstrated by DSC and DTA suggests that elevated temperatures can nevertheless facilitate migration of residual monomeric species without causing measurable deterioration of the polymer framework. This distinction highlights the importance of evaluating both thermal stability and migration behaviour when assessing the overall safety of food-contact polymers.

Styrene Migration at 70°C

The migration experiment conducted at 70°C demonstrated that elevated temperature substantially enhances the release of styrene from polystyrene food packaging into food simulants, confirming that thermal exposure is a primary driver of migration. Although the thermal analyses established that the polymer remained well below its degradation temperature, the increased molecular mobility associated with elevated temperature markedly facilitated the diffusion of residual styrene through the polymer matrix. These findings support the established diffusion-controlled mechanism of migration, whereby increasing temperature expands the free volume of amorphous polymers, accelerates molecular motion and increases the mobility of entrapped low-molecular-weight compounds without requiring chemical degradation of the polymer backbone [61], [62]

The remarkably consistent chromatographic retention times obtained for all simulants demonstrate the analytical reliability of the HPLC method and confirm that the migrated compound remained chemically identical irrespective of the extraction medium. The absence of measurable shifts in retention time indicates that elevated temperature did not alter the chemical identity of the migrant but rather increased the quantity released into the surrounding medium. This consistency strengthens confidence that the measured concentrations accurately represent styrene migration from the packaging material.

Among the simulants, 10% ethanol exhibited the highest styrene concentration, indicating that moderately polar aqueous alcohol systems provide particularly favourable conditions for styrene extraction. Ethanol is widely recognised as an effective food simulant because it possesses sufficient polarity to penetrate the polymer surface while simultaneously exhibiting adequate affinity for hydrophobic organic compounds[63]. This dual characteristic enhances partitioning of styrene from the polymer matrix into the surrounding medium, resulting in greater migration than observed in purely aqueous systems. Similar observations have been reported for polystyrene food-contact materials, where ethanol-containing simulants frequently produce higher migration values than water owing to improved solvent–polymer interactions ([57], [64]).

Vegetable oil also produced relatively high styrene concentrations, reflecting the hydrophobic character of styrene. As a non-polar aromatic hydrocarbon, styrene exhibits considerable affinity for lipid-rich environments, making edible oils effective extraction media for hydrophobic migrants[64]. Nevertheless, the slightly lower concentration observed in vegetable oil compared with 10% ethanol suggests that migration is governed not only by chemical affinity but also by solvent penetration into the polymer matrix. The moderate polarity of aqueous ethanol may promote greater swelling of the amorphous polymer network, thereby facilitating diffusion more effectively than the highly hydrophobic oil phase.

Migration into distilled water remained substantial despite the limited aqueous solubility of styrene. This observation demonstrates that elevated temperature can overcome, at least partially, the unfavourable partitioning of hydrophobic compounds into water by increasing molecular diffusion within the polymer[49]. The enhanced thermal motion of polymer chains generates additional free volume through which residual styrene can migrate before partitioning into the aqueous medium. Consequently, water cannot be regarded as an inert medium under conditions of elevated thermal exposure, particularly when prolonged contact times are involved.

The comparatively lower migration observed in 3% acetic acid suggests that acidic environments may modestly suppress styrene release relative to ethanol and water under identical thermal conditions. Because polystyrene is chemically resistant to weak organic acids, the reduced migration is unlikely to result from polymer degradation. Instead, it probably reflects differences in solvent polarity, partition coefficients and interfacial interactions that influence diffusion from the polymer into the food simulant. Similar solvent-dependent variations have been described for polymer migration studies, where migration behaviour is determined by the combined influence of polymer morphology, migrant solubility and solvent characteristics rather than by a single physicochemical parameter[65], [66]

The pronounced increase in styrene concentration at 70°C compared with lower exposure temperatures demonstrates the dominant influence of temperature on migration kinetics[49], [67] As thermal energy increases, polymer chain segments acquire greater mobility, leading to expansion of intermolecular free volume and accelerated diffusion of residual monomeric species. Importantly, this enhanced migration occurs while the polymer retains its structural integrity, as confirmed by the DSC, DTA and TGA analyses. Thus, elevated temperature increases chemical release primarily by facilitating molecular transport rather than by inducing thermal decomposition of the polymer.

These findings have important implications for the safety of polystyrene food packaging used with hot foods and beverages. Although the material exhibits excellent thermal stability and remains structurally intact under the experimental conditions, elevated temperatures substantially increase consumer exposure to residual styrene through diffusion-controlled migration. Consequently, thermal stability alone should not be interpreted as evidence of migration resistance. A comprehensive assessment of food-contact safety must therefore consider both the physicochemical stability of the polymer and the temperature-dependent mobility of residual low-molecular-weight constituents.

The results further demonstrate that migration is governed by the interaction between polymer properties and food chemistry. Differences among the simulants indicate that solvent composition significantly influences styrene partitioning, with ethanol-containing and lipid-rich media providing more favourable conditions for extraction than acidic aqueous systems. This interplay between temperature, polymer dynamics and food composition underscores the need to evaluate food-contact materials under realistic conditions that reflect the diversity of foods encountered during practical use rather than relying on a single simulant or storage condition alone.

Styrene Migration at 40°C

The migration profile at 40°C demonstrates that moderate thermal exposure is sufficient to enhance styrene release from polystyrene food packaging, although to a lesser extent than observed at 70°C. This finding indicates that diffusion of residual styrene is not restricted to high-temperature conditions but increases progressively as molecular mobility within the polymer matrix rises above ambient levels. The temperatures employed remain substantially below those associated with thermal decomposition, confirming that the observed migration results from temperature-enhanced diffusion rather than degradation of the polymer backbone. This interpretation is fully consistent with the DSC, DTA and TGA analyses, which showed that increased chain mobility precedes any measurable structural decomposition[68].

The highly consistent chromatographic retention times recorded across all food simulants confirm the analytical robustness of the HPLC method and demonstrate that the migrating compound remained chemically unchanged irrespective of solvent composition. The absence of retention-time variation indicates that the increased concentrations measured at 40°C reflect quantitative changes in styrene release rather than the formation of degradation products or alternative migration compounds. Such chromatographic stability strengthens confidence in the reliability and reproducibility of the migration measurements.

Distilled water exhibited the highest styrene concentration at 40°C, indicating that moderate heating substantially increases migration even into an aqueous medium despite the relatively low water solubility of styrene. This behaviour suggests that the effect of temperature on polymer diffusion becomes sufficiently pronounced to overcome limitations imposed by solvent polarity. Increased thermal motion within the amorphous polymer matrix enlarges intermolecular free volume, thereby facilitating the transport of residual styrene molecules to the polymer–liquid interface where partitioning into the aqueous phase can occur. The findings demonstrate that water should not be regarded as a negligible extraction medium under conditions involving prolonged exposure to moderately elevated temperatures.

Migration into 3% acetic acid was only slightly lower than that observed in distilled water, indicating that weak acidity exerts relatively little influence on styrene release under moderate thermal conditions. Because polystyrene exhibits excellent chemical resistance to dilute organic acids, the migration behaviour is more appropriately explained by diffusional processes than by solvent-induced chemical modification of the polymer. The similarity between water and acetic acid suggests that the modest increase in molecular mobility produced at 40°C plays a more dominant role in controlling migration than minor differences in solvent chemistry.

Vegetable oil produced intermediate styrene concentrations, consistent with the hydrophobic nature of styrene and its affinity for lipid-rich media. However, unlike the pattern observed at 70°C, vegetable oil did not produce the highest migration at this temperature. This finding indicates that solvent affinity alone does not determine migration behaviour. Instead, migration reflects the combined influence of polymer swelling, molecular diffusion and partition equilibrium between the polymer matrix and the contacting medium. At 40°C, the increase in chain mobility may not be sufficient for the non-polar oil phase to fully

exploit its greater chemical affinity for styrene, resulting in migration values comparable with those observed in aqueous simulants.

The relatively lower concentration measured in 10% ethanol contrasts with its dominant extraction capacity at 70°C and illustrates the interactive effects of temperature and solvent composition on migration kinetics. Although aqueous ethanol is capable of penetrating amorphous polymer networks and dissolving hydrophobic compounds, its extraction efficiency appears to increase more markedly at higher temperatures where enhanced polymer relaxation facilitates solvent penetration. This observation suggests that the influence of solvent composition becomes increasingly pronounced as molecular mobility within the polymer continues to rise.

Comparison with the 70°C results reveals a clear temperature-dependent reduction in styrene migration across all simulants, supporting the conclusion that migration follows thermally activated diffusion kinetics. As temperature decreases, segmental motion of the polymer chains is reduced, limiting the expansion of free volume and slowing the transport of residual styrene through the polymer matrix. Nevertheless, the measurable concentrations detected at 40°C demonstrate that migration remains an active process under conditions representative of warm food storage, reheating or prolonged exposure to elevated ambient temperatures. Consequently, appreciable styrene release cannot be considered exclusive to extreme heating conditions.

The migration behaviour observed at 40°C also highlights the importance of polymer morphology in determining chemical release. The amorphous structure of polystyrene permits gradual increases in chain mobility with rising temperature, allowing diffusion rates to increase continuously rather than abruptly. This behaviour explains the progressive rather than exponential increase in styrene concentrations across the experimental temperature range and is consistent with established models describing migration from amorphous food-contact polymers[57], [69]

From a food safety perspective, these findings demonstrate that moderate heating conditions commonly encountered during food preparation, transportation and storage may significantly increase consumer exposure to residual styrene even in the absence of visible deformation or deterioration of the packaging material[49]. The excellent thermal stability demonstrated by DSC, DTA and TGA should therefore not be interpreted as evidence of negligible migration potential. Instead, thermal stability and migration behaviour represent complementary but distinct aspects of material performance that must both be considered during safety evaluation.

Styrene Migration at 25°C

The migration behaviour observed at 25°C represents the baseline release of styrene under ambient storage conditions and demonstrates that residual monomer migration occurs even in the absence of elevated thermal stress[69]. Although the concentrations detected were the lowest among all temperature conditions investigated, measurable quantities of styrene were identified in every food simulant, indicating that diffusion of residual monomer is an inherent characteristic of polystyrene food

packaging. These findings confirm that migration is not exclusively a consequence of heating but is a continuous diffusion-driven process that proceeds whenever concentration gradients exist between the polymer matrix and the contacting medium.

The uniform chromatographic retention times obtained across all simulants further confirm the specificity and reproducibility of the analytical method. The absence of retention-time variation indicates that the migrating compound remained chemically unchanged under ambient conditions and that differences in measured concentrations reflect variations in migration behaviour rather than analytical inconsistency or chemical transformation. This chromatographic stability supports the conclusion that the detected analyte represents residual styrene released directly from the polymer matrix.

Distilled water and 10% ethanol produced the highest styrene concentrations at room temperature, with both simulants exhibiting essentially equivalent migration levels. This similarity suggests that under ambient conditions the influence of solvent chemistry is relatively limited because molecular diffusion within the polymer remains the principal rate-limiting step. Restricted segmental mobility of the amorphous polymer chains limits the transport of residual styrene to the polymer surface, thereby minimising the influence of differences in solvent polarity or extraction capacity. Consequently, although ethanol generally exhibits greater affinity for hydrophobic organic compounds[70], its enhanced extraction potential becomes less apparent when diffusion through the polymer matrix proceeds slowly.

Vegetable oil yielded slightly lower styrene concentrations despite the hydrophobic nature of styrene. Under ambient conditions, the limited mobility of polymer chains appears to constrain diffusion to such an extent that the favourable partitioning of styrene into lipid-rich media cannot be fully exploited. This observation demonstrates that migration is governed by sequential processes involving diffusion through the polymer followed by partitioning into the contacting medium[66]. When diffusion remains slow, solvent affinity alone cannot substantially increase overall migration.

The lowest migration was observed in 3% acetic acid, suggesting that dilute acidic environments provide comparatively less favourable conditions for styrene extraction under ambient storage conditions. Because polystyrene is chemically resistant to weak organic acids[31], the reduced migration is unlikely to arise from chemical interaction between the polymer and the simulant. Instead, it probably reflects differences in partition equilibrium and solvent–polymer interactions that limit transfer of styrene into the acidic medium. Similar solvent-dependent variations have been described in migration studies of food-contact polymers, where both diffusional transport and solvent characteristics contribute to overall migration behaviour (Royuela et al., 2024; Sepúlveda-Carter et al., 2025).

Comparison of the three temperature conditions demonstrates a clear and progressive increase in styrene migration with increasing thermal exposure. The consistently lower concentrations measured at 25°C indicate that restricted molecular motion within the polymer matrix substantially reduces diffusion rates. At ambient temperature, polymer chain segments remain predominantly in the glassy state, with limited free volume available for migration of residual low-molecular-weight compounds. Consequently, transport of styrene through the polymer proceeds slowly, resulting in comparatively low concentrations

in all food simulants. This behaviour agrees with established diffusion theory for amorphous polymers, in which molecular mobility increases continuously with temperature, producing corresponding increases in migration rates[49], [71]

Despite the relatively low concentrations observed, the detection of styrene in every simulant has important implications for food-contact safety. The findings demonstrate that residual styrene remains sufficiently mobile to migrate under routine storage conditions, particularly during prolonged contact between packaging materials and food. While the measured concentrations were markedly lower than those recorded at 40 and 70°C, the cumulative nature of repeated exposure means that ambient migration cannot be disregarded when assessing long-term consumer exposure[8].

The ambient migration results also complement the thermal characterisation presented earlier in this study. DSC and DTA demonstrated that polymer chain mobility increases progressively with temperature, whereas TGA confirmed that structural degradation does not occur within the experimental temperature range. The migration behaviour at 25°C represents the lower limit of this diffusion continuum, where the polymer remains rigid and molecular transport is strongly constrained. As temperature subsequently increases to 40 and 70°C, greater chain mobility and expansion of free volume accelerate diffusion without requiring degradation of the polymer backbone. Thus, the migration experiments provide experimental validation of the mechanisms predicted by the thermal analyses.

Conclusion

The integration of elemental, spectroscopic, thermal and migration analyses provides a comprehensive understanding of the factors governing the performance of polystyrene food packaging. SEM–EDS demonstrated that the material consists predominantly of a carbon-rich styrene polymer matrix containing minor inorganic constituents associated with industrial formulation and manufacture. FTIR subsequently confirmed the preservation of the characteristic aromatic molecular architecture of polystyrene, while DSC, DTA and TGA collectively established that the material possesses excellent thermal stability and remains structurally intact across temperatures relevant to food packaging applications.

Despite this high thermal stability, the migration experiments unequivocally demonstrate that structural integrity does not preclude chemical release. Instead, styrene migration is governed primarily by diffusion through an amorphous polymer matrix whose molecular mobility increases progressively with temperature. As thermal energy rises, greater segmental motion expands intermolecular free volume, thereby facilitating transport of residual styrene to the polymer surface where partitioning into food simulants occurs. The progressive increase in migration from 25°C to 40°C and 70°C therefore reflects enhanced diffusional transport rather than thermal degradation of the polymer itself.

The influence of food simulant composition further illustrates that migration is controlled by a combination of polymer dynamics and solvent properties. Variations among distilled water, ethanol, vegetable oil and acetic acid indicate that solvent polarity, affinity for styrene and polymer–solvent

interactions all contribute to the extent of migration. However, the consistent temperature-dependent increase observed across every simulant confirms that thermal activation remains the dominant factor regulating styrene release.

Collectively, these findings demonstrate that evaluation of food-contact polymers should extend beyond conventional assessments of thermal stability to include diffusion-controlled migration behaviour under realistic conditions of use. The investigated polystyrene packaging exhibits excellent resistance to thermal degradation, yet residual styrene remains sufficiently mobile to migrate into representative food simulants, particularly under elevated temperatures. This integrated physicochemical assessment therefore provides a mechanistic framework linking molecular structure, thermal behaviour and migration kinetics, offering valuable insights for material selection, food-contact safety assessment and the development of safer polymer formulations with reduced migration potential.

Declarations

Author Contribution

Author Contributions E.A. conceived the study, conducted the experimental work, performed data collection and analysis, and wrote the first draft of the manuscript. Oy.A. contributed to the study design, supervised the research, interpreted the data, critically revised the manuscript for important intellectual content, and provided overall project oversight. Ol.A. contributed to the methodology, data interpretation, manuscript editing, and critical review of the final manuscript. All authors reviewed, approved, and agreed to the published version of the manuscript.

Funding Declaration

The authors received no financial support from any funding agency in the public, commercial, or not-for-profit sectors for the research, authorship, and/or publication of this article.

Human Ethics and Consent to Participate

Not applicable. This study did not involve human participants, human tissues, human data, or human biological materials. Therefore, ethical approval and informed consent to participate were not required.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Consent to Publish

Not Applicable

References

1. El-Ziney MG. Migration Levels of Monostyrene from Polystyrene Containers to Dairy Products. *MOJ Food Process Technol.* Oct. 2016;3(2). 10.15406/mojfpt.2016.03.00066.
2. Rashid M, Gaikwad KK, Esatbeyoglu T. Introduction to Food Packaging Technology, in *Apple Academic Press eBooks*, 2025, pp. 1–30. 10.1201/9781003597438-1
3. Shahzadi C, Aielli L, Costantini E, Reale M, Carlo PD. Breaching Barriers: Microplastic Translocation into Human Body Through Food and Implications for Neurodegeneration. *Curr Pollution Rep.* Oct. 2025;11(1). 10.1007/s40726-025-00386-2.
4. Yousif E, Haddad R. Photodegradation and photostabilization of polymers, especially polystyrene: review, *SpringerPlus*, vol. 2, no. 1, pp. 398–398, Aug. 2013, 10.1186/2193-1801-2-398
5. Adeyemi O, Akpomede EC. Enhanced petroleum hydrocarbon removal via integrated nano-phytoremediation: Synergistic coupling of water hyacinth and zero-valent iron nanoparticles. Apr 03, 2026.
6. Adeyemi O, Modesta OC. Ultrafine Particle–Driven Toxicity from Plastic Waste Combustion: Haematological Disruption and Redox Imbalance in Experimental Rats. Zenodo (CERN Eur Organ Nuclear Research) Apr. 2026. 10.5281/zenodo.19563461.
7. Gupta RK et al. Sept., Migration of Chemical Compounds from Packaging Materials into Packaged Foods: Interaction, Mechanism, Assessment, and Regulations, *Foods*, vol. 13, no. 19, pp. 3125–3125, 2024, 10.3390/foods13193125
8. Norte TG, Ramos F, Nerín C, Sanches-Silva A. Styrene migration from food contact materials, *Food Chemistry*, vol. 501, pp. 147512–147512, Dec. 2025, 10.1016/j.foodchem.2025.147512
9. Ding B, et al. Unveiling Hidden Health Risks: Machine Learning Enhanced Modeling of Plastic Additive Release Kinetics in Fresh Produce Packaging. *Environ Sci Technol.* June 2025;59:12268–78. 10.1021/acs.est.5c02821.
10. van der Linden N, Montanari F, Luning P. Mapping risk assessment and management status of recycled food contact materials in Europe - risk analysis in a circular economy, *Trends in Food Science & Technology*, vol. 172, pp. 105674–105674, Mar. 2026, 10.1016/j.tifs.2026.105674
11. Guazzotti V, Hendrich V, Gruner A, Fiedler D, Störmer Á, Welle F. Styrene Migration from Polystyrene for Food Contact: A Case Study on the Processing Chain of Yoghurt Pots, *Applied Sciences*, vol. 14, no. 19, pp. 9056–9056, Oct. 2024, 10.3390/app14199056
12. Guazzotti V, Hendrich V, Gruner A, Störmer Á, Welle F. Styrene Monomer Levels in Polystyrene-Packed Dairy Products from the Market versus Simulated Migration Testing. *Foods.* July 2023;12(13):2609–2609. 10.3390/foods12132609.
13. Beneventi E, Goldbeck C, Zellmer S, Merkel S, Luch A, Tietz T. Migration of styrene oligomers from food contact materials: in silico prediction of possible genotoxicity. *Arch Toxicol.* Aug. 2022;96(11):3013–32. 10.1007/s00204-022-03350-x.
14. Wang J, Lee J, Kwon EE, Jeong S. Quantitative analysis of polystyrene microplastic and styrene monomer released from plastic food containers. *Heliyon.* Apr. 2023;9(5). 10.1016/j.heliyon.2023.e15787.

15. Seref N, Çufaoğlu G. Food Packaging and Chemical Migration: A Food Safety Perspective. *J Food Sci.* May 2025;90(5). 10.1111/1750-3841.70265.
16. Tsochatzis E, Lopes JA, Corredig M. Chemical testing of mechanically recycled polyethylene terephthalate for food packaging in the European Union, *Resources Conservation and Recycling*, vol. 179, pp. 106096–106096, Dec. 2021, 10.1016/j.resconrec.2021.106096
17. Velásquez E et al. Dec., Repetitive mechanical recycling of post-consumer high impact polystyrene from yogurt cups: A pilot-scale performance assessment at different reprocessing cycles, *Resources Conservation and Recycling*, vol. 202, pp. 107368–107368, 2023, 10.1016/j.resconrec.2023.107368
18. Basha NNJ, Hafiz NBA, Osman MS, Bakar NFA. Unveiling the noxious effect of polystyrene microplastics in aquatic ecosystems and their toxicological behavior on fishes and microalgae. *Front Toxicol.* May 2023;5:1135081–1135081. 10.3389/ftox.2023.1135081.
19. Farouq R. Functionalized graphene/polystyrene composite, green synthesis and characterization. *Sci Rep.* Dec. 2022;12(1):21757–21757. 10.1038/s41598-022-26270-3.
20. Thakur S, Verma A, Sharma B, Chaudhary J, Tamulevičius S, Thakur VK. Recent developments in recycling of polystyrene based plastics. *Curr Opin Green Sustainable Chem.* Mar. 2018;13:32–8. 10.1016/j.cogsc.2018.03.011.
21. Hurley R, et al. Production and characterisation of environmentally relevant microplastic test materials derived from agricultural plastics. *Sci Total Environ.* June 2024;946:174325–174325. 10.1016/j.scitotenv.2024.174325.
22. Myalenko D, Федотова ОБ, Agarkov AA, Sirotin S, Poletaeva P. Tensile and Structural Properties of Antioxidant- and CaCO₃-Modified Polyethylene Films, *Polymers*, vol. 17, no. 16, pp. 2182–2182, Aug. 2025, 10.3390/polym17162182
23. Cherif GA, Kerkour A, Mouloud A, Benmohad KF, Bouanane Z. Structure–Property Relationships in Recycled HDPE Composites: Role of Nanofiller/Antioxidant Treatment on Mechanical, Rheological, and Diffusion Properties. *J Appl Polym Sci.* Mar. 2026. 10.1002/app.70651.
24. Binda G, et al. A screening of metal(loid) content in conventional and compostable plastic polymers: understanding the sources and the connected environmental implications. *Environ Pollut.* May 2025;375:126364–126364. 10.1016/j.envpol.2025.126364.
25. González-Torres P, García-Ruiz Á, Rubia MDL. Impact of thermal treatment and storage on degradation and migration in edible seed oils packaged in PET. *J Stored Prod Res.* May 2025;113:102679–102679. 10.1016/j.jspr.2025.102679.
26. Xia D, Zhao A, Lu R, Zhang D, Peng Z, Sun Y. Atmospheric Emissions of Short- and Medium-Chain Chlorinated Paraffins from Polyvinyl Chloride/Plastics and Rubber Products Incineration, *ACS ES&T Air*, Mar. 2026, 10.1021/acsestair.5c00477
27. Scharek VM, Kröger T, Keil K, Traub H, Meermann B. A new elemental analytical approach for microplastic sum parameter analysis—ETV/ICP-MS with CO₂. *Anal Bioanal Chem.* Oct. 2025. 10.1007/s00216-025-06146-x.

28. Radhakrishnan H, Mohammed AABA, Coffman I, Bai X. Influence of functional additives, fillers, and pigments on thermal and catalytic pyrolysis of polyethylene for waste plastic upcycling. *Green Chem.* Jan. 2025;27(20):5861–82. 10.1039/d5gc00688k.
29. Royuela D, et al. Pyrolysis of polystyrene using low-cost natural catalysts: Production and characterisation of styrene-rich pyro-oils. *J Anal Appl Pyrol.* Aug. 2024;182:106690–106690. 10.1016/j.jaap.2024.106690.
30. Rabhi A et al. Dec., Thermal and Mechanical Performances Optimization of Plaster–Polystyrene Bio-Composites for Building Applications, *CivilEng*, vol. 5, no. 4, pp. 1172–1184, 2024, 10.3390/civileng5040057
31. Singh A, Chauhan A, Gaur R. A comprehensive review on the synthesis, properties, environmental impacts, and chemiluminescence applications of polystyrene (PS). *Discover Chem.* Mar. 2025;2(1). 10.1007/s44371-025-00125-y.
32. Pfaendner R. Polymer Additives. pp. 409–44, Oct. 28, 2025. 10.1002/9781119820123.ch11
33. Monclús L, et al. Mapping the chemical complexity of plastics. *Nature.* July 2025;643(8071):349–55. 10.1038/s41586-025-09184-8.
34. Dobrotă D, Bărbușiu A-M, Sava G-A, Oleksik V, Functional Additives in Automotive Polymer Matrices: Compatibility, Mechanisms, and, Challenges I. *Polymers*, vol. 17, no. 17, pp. 2328–2328, Aug. 2025, 10.3390/polym17172328
35. Fajdek-Bieda A, Wróblewska A. The Use of Natural Minerals as Reinforcements in Mineral-Reinforced Polymers: A Review of Current Developments and Prospects, *PubMed Central*, vol. 16, no. 17, pp. 2505–2505, Sept. 2024, 10.3390/polym16172505
36. Artchomphoo J, Saijun D, Booncharoen K, Sungsee P, Rattanapan S. Effects of Hybrid Filler and Mixing Equipment on the Mechanical and Thermal Properties of NR/EPDM Rubber Blends, *Indonesian Journal of Chemistry*, vol. 24, no. 4, pp. 1195–1195, Aug. 2024, 10.22146/ijc.94097
37. Infurna G et al. Dec., Sustainable and efficient metal hydroxides as halogen-free flame-retardant additives in polyolefin-based composites for cable sheathing applications, *Journal of Physics and Chemistry of Solids*, vol. 211, pp. 113458–113458, 2025, 10.1016/j.jpcs.2025.113458
38. Corre ML, Pierson-Wickmann A, Guéguen B, Pattier M, Rabiller-Baudry M, Dia A. From elements to isotopes: Fingerprinting consumer plastics. *Talanta.* Jan. 2026;302:129404–129404. 10.1016/j.talanta.2026.129404.
39. Eriksen MK, Pivnenko K, Olsson M, Astrup TF. Contamination in plastic recycling: Influence of metals on the quality of reprocessed plastic, *Waste Management*, vol. 79, pp. 595–606, Sept. 2018, 10.1016/j.wasman.2018.08.007
40. Bouhadi N, Boudriche L, Ghaliaoui N, Abderrahmane ON. Food Packaging Materials: Risks of Contamination. *Food Drug Saf.* Jan. 2026;3(1):77–87. 10.55121/fds.v3i1.892.
41. Caux B, Jores CDS, Abou-Naccoul R, West C. From extraction to detection: An analytical journey of plastic additives and their migrations. *TRAC Trends Anal Chem.* July 2025;191:118373–118373. 10.1016/j.trac.2025.118373.

42. Guazzotti V, Welle F. Recycling of Post-Consumer Polystyrene Packaging Waste into New Food Packaging Applications—Part 3: Initial Contamination Levels in Washed Flakes from Europe, *Recycling*, vol. 10, no. 2, pp. 37–37, Mar. 2025, 10.3390/recycling10020037
43. Yıldırım S. Plastik Biyobozunması: Mikrobiyal Enzimlerin Potansiyeli, *DergiPark (Istanbul University)*, June 2025, Accessed: Mar. 2026. [Online]. Available: <https://dergipark.org.tr/tr/pub/gjohbs/issue/93950/1722176>
44. Genuino HC, van Eijk MCP. Predicting Elemental Contaminant Levels in Household Plastic Packaging Waste: A Hierarchical Model for Optimizing Pyrolysis Feedstock. *ACS Sustain Chem Eng*. July 2025;13(30):11784–95. 10.1021/acssuschemeng.5c01817.
45. Estremera C, Blázquez-Martín J, Aznar M, Nerín C, Domeño C. MS-DIAL as efficient tool for the food safety assessment of volatile substances in disposable tableware, *Zaguan (University of Zaragoza Repository)*, vol. 49, pp. 101528–101528, May 2025, 10.1016/j.fpsl.2025.101528
46. Böke JS, Popp J, Krafft C. Optical photothermal infrared spectroscopy with simultaneously acquired Raman spectroscopy for two-dimensional microplastic identification. *Sci Rep*. Nov. 2022;12(1). 10.1038/s41598-022-23318-2.
47. Smith BC. The Infrared Spectra of Polymers III: Hydrocarbon Polymers, *Spectroscopy*, pp. 22–25, Nov. 2021, 10.56530/spectroscopy.mh7872q7
48. Giakoumakis N et al. Nov., Total revalorization of high impact polystyrene (HIPS): enhancing styrene recovery and upcycling of the rubber phase, *Green Chemistry*, vol. 26, no. 1, pp. 340–352, 2023, 10.1039/d3gc02407e
49. Ajaj A, et al. An Insight into the Growing Concerns of Styrene Monomer and Poly(Styrene) Fragment Migration into Food and Drink Simulants from Poly(Styrene) Packaging. *Foods*. May 2021;10(5):1136–1136. 10.3390/foods10051136.
50. Li H, et al. Expanding plastics recycling technologies: chemical aspects, technology status and challenges. *Green Chem*. Jan. 2022;24(23):8899–9002. 10.1039/d2gc02588d.
51. Guaita M. Thermal Degradation of Polystyrene. *Br Polym J*. July 1986;18(4):226–30. 10.1002/pi.4980180405.
52. Yoshida E. Vacuum pyrolysis depolymerization of waste polystyrene foam into high-purity styrene using a spirit lamp flame for convenient chemical recycling, *RSC Sustainability*, vol. 1, no. 8, pp. 2058–2065, Jan. 2023, 10.1039/d3su00207a
53. Huang J, Zeng G, Li XS, Cheng X, Tong H. Theoretical studies on bond dissociation enthalpies for model compounds of typical plastic polymers, in *IOP Conference Series Earth and Environmental Science*, IOP Publishing, July 2018, pp. 12029–12029. 10.1088/1755-1315/167/1/012029
54. Vallejos S et al. Nov., From Classical to Advanced Use of Polymers in Food and Beverage Applications, *Polymers*, vol. 14, no. 22, pp. 4954–4954, 2022, 10.3390/polym14224954
55. Lion A, Johlitz M. Modelling of temperature-related phenomena in polymers. *Acta Mech*. Mar. 2026. 10.1007/s00707-026-04652-2.

56. Zeng W, Chow WK, Yao B. Chemical kinetics and mechanism of polystyrene thermal decomposition, *PolyU Institutional Research Archive (Hong Kong Polytechnic University)*, vol. 7, pp. 128–128, Jan. 2007, Accessed: Oct. 2025. [Online]. Available: <http://hdl.handle.net/10397/45227>
57. Paraskevopoulou D, Achilias DS, Paraskevopoulou A. Migration of styrene from plastic packaging based on polystyrene into food simulants, *Polymer International*, vol. 61, no. 1, pp. 141–148, Sept. 2011, 10.1002/pi.3161
58. Xuan W, Yan S, Dong Y. Exploration of Pyrolysis Behaviors of Waste Plastics (Polypropylene Plastic/Polyethylene Plastic/Polystyrene Plastic): Macro-Thermal Kinetics and Micro-Pyrolysis Mechanism, *Processes*, vol. 11, no. 9, pp. 2764–2764, Sept. 2023, 10.3390/pr11092764
59. Gurbanov MA, Guliyeva UA, Mirzazada EV. Study of the Thermal Pyrolysis of Packaging Materials by Derivatographic Methods, *Advanced materials research*, vol. 1185, pp. 49–60, Dec. 2025, 10.4028/p-dum8bd
60. Saad JM, Williams PT, Zhang YS, Yao D, Yang H, Zhou H. Comparison of waste plastics pyrolysis under nitrogen and carbon dioxide atmospheres: A thermogravimetric and kinetic study. *J Anal Appl Pyrol.* May 2021;156:105135–105135. 10.1016/j.jaap.2021.105135.
61. Fang X, Vitrac O. Predicting diffusion coefficients of chemicals in and through packaging materials, *Critical Reviews in Food Science and Nutrition*, vol. 57, no. 2, pp. 275–312, Apr. 2015, 10.1080/10408398.2013.849654
62. Wang Z. Effect of Free Volume in Polyolefins on Diffusion Coefficient of Migratory Substances. Jan. 2008.
63. Guazzotti V, Gruner A, Juric M, Hendrich V, Störmer Á, Welle F. Migration Testing of GPPS and HIPS Polymers: Swelling Effect Caused by Food Simulants Compared to Real Foods, *Molecules*, vol. 27, no. 3, pp. 823–823, Jan. 2022, 10.3390/molecules27030823
64. Tawfik MS, Huyghebaert A. Polystyrene cups and containers: Styrene migration. *Food Addit Contam.* July 1998;15(5):592–9. 10.1080/02652039809374686.
65. Seyedalizadeh M, Abdolmaleki F. The Effect of Microwave on Migration of Styrene Monomer Polystyrene Food Packaging and Compared to other Thermal Processes, *Journal of Food Biosciences and Technology*, vol. 9, no. 1, pp. 69–76, Jan. 2019, Accessed: Oct. 2025. [Online]. Available: http://jfbt.srbiau.ac.ir/article_13161_1cbc1d730ed0ae6c56f51b2f18f655b6.pdf
66. Dawson P, Seydim AC, Hirt DE. Styrene Monomer Migration from Expanded Polystyrene Into Food Acids and Ethanol. *J Food Res.* May 2020;9(3):39–39. 10.5539/jfr.v9n3p39.
67. bin MS, Shayuti M, Shafiq M. The Effect of High Temperature on Styrene Monomer Migration from Polystyrene Cup, Jan. 2008, Accessed: Nov. 2025. [Online]. Available: <http://utpedia.utp.edu.my/250/>
68. He L, et al. Highly robust supramolecular polymer networks crosslinked by a tiny amount of metallacycles. *Nat Commun.* Apr. 2024;15(1):3050–3050. 10.1038/s41467-024-47333-1.
69. Amirshaghaghi Z, Emam-Djomeh Z, Oromiehie A. Studies of Migration of Styrene Monomer from Polystyrene Packaging into the Food Simulant, Jan. 2011, Accessed: Nov. 2025. [Online]. Available:

http://www.sid.ir/en/VEWSSID/J_pdf/102420110405.pdf

70. Larasati A, Fowler GD, Graham N. Chemical regeneration of granular activated carbon: preliminary evaluation of alternative regenerant solutions, *Environmental Science Water Research & Technology*, vol. 6, no. 8, pp. 2043–2056, Jan. 2020, 10.1039/d0ew00328j
71. Teuten EL, et al. Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Trans Royal Soc B Biol Sci.* June 2009;364(1526):2027–45. 10.1098/rstb.2008.0284.