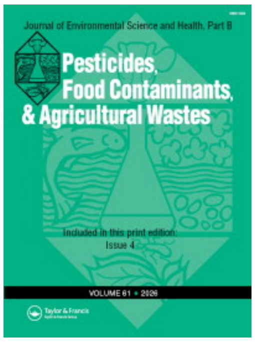

Taylor & Francis
Taylor & Francis Group

Journal of Environmental Science and Health, Part B

Pesticides, Food Contaminants, and Agricultural Wastes

ISSN: 0360-1234 (Print) 1532-4109 (Online) Journal homepage: www.tandfonline.com/journals/lesb20

Migration of phthalates, bisphenols, photoinitiators, and perfluorinated compounds in polyethylene and polystyrene based beverage cups

Sezer Kıralan , İsra Toptancı & Cansu Sezer

To cite this article: Sezer Kıralan , İsra Toptancı & Cansu Sezer (2026) Migration of phthalates, bisphenols, photoinitiators, and perfluorinated compounds in polyethylene and polystyrene based beverage cups, Journal of Environmental Science and Health, Part B, 61:4, 176-184, DOI: 10.1080/03601234.2026.2633932

To link to this article: https://doi.org/10.1080/03601234.2026.2633932

JOURNAL OF ENVIRONMENTAL SCIENCE AND HEALTH, PART B
2026, VOL. 61, NO. 4, 176–184
https://doi.org/10.1080/03601234.2026.2633932

Migration of phthalates, bisphenols, photoinitiators, and perfluorinated compounds in polyethylene and polystyrene based beverage cups

Sezer Kıralan[a], İsra Toptancı[b], and Cansu Sezer[a]

[a]Department of Food Engineering, Faculty of Engineering, Balikesir University, Balikesir, Turkey; [b]Department of Food Contact Material and Dioxin, Istanbul Food Control Laboratory, Istanbul, Turkey

ABSTRACT

Disposable paper cups are widely used for consuming beverages, particularly hot drinks, in daily life. However, concerns regarding the migration of hazardous chemicals from these cups into beverages have been largely overlooked. This study investigates the presence of phthalates, bisphenols, photoinitiators (PIs), and two perfluorinated compounds (PFC) in polyethylene and polystyrene based beverage cups from Turkey. Potential migrants were quantified using liquid chromatography–tandem mass spectrometry (LC–MS/MS) in a total of 40 cup samples. Among the phthalates analyzed, di(2-ethylhexyl) phthalate (DEHP) was the most prevalent, with concentrations reaching up to 0.95 mg/kg. Bisphenol A (BPA) was the dominant bisphenol, detected at levels between 0.01 and 0.02 mg/kg. Five photoinitiators—benzophenone, 1-hydroxycyclohexyl phenyl ketone, 4-methylbenzophenone, 4-hydroxybenzophenone, and ethyl 4-dimethylaminobenzoate—were frequently identified, indicating the contribution of printing inks and surface coatings as contamination sources. In addition, perfluorooctanoic acid (PFOA) was detected in two samples, highlighting the potential presence of PFOA in disposable food-contact materials. The results underscore the need for continued surveillance of food-contact materials and the implementation of stricter regulatory controls to reduce long-term consumer health risks.

ARTICLE HISTORY
Received 8 December 2025
Accepted 14 February 2026

KEYWORDS
Beverage cups; phthalates; bisphenols; photoinitiators; perfluorinated compounds

Introduction

Paper and paperboard are extensively used in food packaging, particularly for disposable products that come into direct contact with food.[1] Among these, disposable cups are one of the most prevalent single-use plastic items, commonly composed of polyethylene-coated paper or polymer copolymers, primarily used for serving hot beverages.[2] Typically, disposable paper cups consist of 90–95% paper by weight, with the remaining 5–10% comprising a hydrophobic plastic coating to prevent liquid absorption.[2] The global consumption of disposable paper cups is substantial; for instance, in the UK alone, approximately 7 million cups are daily used.[3] Owing to their extensive use and direct contact with hot liquids, disposable cups have become a growing focus of research into chemical migration and consumer exposure.

Disposable beverage cups are far from being simple monolayer materials and are, in fact, complex multilayer materials. They are typically composed of a fibrous cellulose-based paperboard substrate, a low-polarity polymer layer (primarily LDPE), and sometimes an additional tie layer to improve interlayer adhesion. The fibrous nature of paper promotes sorption and diffusion of low molecular weight compounds, while the polymer layer controls barrier properties and diffusion resistance. The multilayer structure of these materials has a profound effect on migration rates and selectivity, especially when exposed to high temperatures, as in the case of hot beverages.[4]

Food contact materials (FCMs) may contain both intentionally added substances (IAS), such as plasticizers, stabilizers, and photoinitiators, and non-intentionally added substances (NIAS), including impurities, degradation products, reaction by-products, and contaminants formed during processing While IAS are generally regulated under specific migration limits, NIAS often remain toxicologically insufficiently characterized and analytically challenging to identify, representing a significant uncertainty in risk assessment. Therefore, the selection of phthalates, bisphenols, photoinitiators, and PFCs in the present study was based on their widespread industrial use in paper- and polymer-based FCMs, documented migration potential, toxicological relevance, and increasing regulatory scrutiny.[5,6]

During manufacturing, various additives including plasticizers and photoinitiators (PIs) are incorporated to enhance durability, flexibility, color stability, and antimicrobial properties.[2,7] It is now well established that these additives can migrate from food-contact materials into beverages, particularly under elevated temperatures, raising concerns about potential health effects.[8] Migration is a diffusion-controlled process that is also influenced by temperature and the

CONTACT Sezer Kıralan sezertrhn@gmail.com Department of Food Engineering, Faculty of Engineering, Balikesir University, Balikesir 10145, Turkey.
Supplemental data for this article can be accessed online at https://doi.org/10.1080/03601234.2026.2633932.

physicochemical properties of the migrant, including molecular weight and volatility. When temperature increases, molecular mobility is enhanced within the polymer matrix, thus accelerating migration. The solubility and partitioning properties determine how a substance is distributed between two media.[6] Consequently, the migration of specific groups of contaminants from disposable food-contact materials especially phthalates,[9] bisphenols,[10] photoinitiators,[11] and microplastics represents a significant concern for human health, yet the available scientific evidence remains inadequate.[7,12–14]

Phthalate esters are commonly used as plasticizers[15] in food packaging materials, and studies have demonstrated their migration from paper-based food-contact materials, with migration levels depending on simulant composition; among the investigated compounds, DEHA exhibited the highest migration.[9] In addition, photoinitiators employed in UV-curable printing inks have been identified as potential migrants from food packaging material.[16] Bisphenols, particularly bisphenol A (BPA), are widely used in plastic production[17,18] and have been detected in paper-based food-contact materials, with studies reporting measurable BPA migration into food.[8] In addition, perfluorinated compounds (PFCs) a group of highly persistent environmental contaminants, have been identified in food-contact materials, raising increasing concern regarding consumer exposure. This was the first study presenting the presence of PFOA in paper cups produced in Turkey.

This study investigated the migration rates of a broad range of contaminants (phthalates, bisphenols, photoinitiators, and PFCs) in beverage cups sold in Turkey using liquid chromatography–tandem mass spectrometry (LC–MS/MS). To the best of our current knowledge, this is the first study in Turkey revealing the migration of various contaminants (phthalates, photoinitiators, bisphenols, and PFCs) from polyethylene and polystyrene-based beverage cups.

Materials and methods

Samples

All 40 samples used in the study were collected in year 2023 from local market of Eskişehir Turkey. The samples can further be divided into six cup categories; printed paper cup, unprinted paper cup, colored paper cup, foam cup, craft paper cup and plastic tumbler. The polymer types were selected based on materials commonly used in disposable beverage cups. Detailed information about cups were given in Table S1. Each category was analyzed in triplicate ($n=3$). The phthalate and photoinitiator concentrations are shown in mg/kg simulant of cups.

Chemicals and reagents

All the analytical Bisphenol and Photoinitiator standards (Table S2) were obtained from Merck (Darmstadt, Germany). The standards of 6 phthalate ester standards (Table S2) were purchased from Dr. Ehrenstorfer, ensuring a standard purity level of over 98%. The analytical PFOA-PFOS standards were obtained from Sigma-Aldrich (St. Louis, MO, USA). Ultrapure water was prepared using a Milli-Q filter system (Millipore, Bedford, MA, USA).

Sample preparation

Two different sample preparation methods were employed to accommodate the distinct analytical requirements of bisphenols, photoinitiators, phthalate esters, and PFCs. To avoid cross-contamination during sample preparation and analysis, all procedures were conducted using pre-clean equipment and under controlled laboratory conditions. In addition, blank control experiments were performed by analyzing simulants under the same conditions as the samples.

- **Bisphenol Analysis:** The sample preparation simulated the real-life use of hot beverages. A volume of 200 mL of hot water (≈95 °C) was poured into beverage cups and left uncovered for 15 minutes to mimic daily usage conditions. The temperature and exposure time were selected to reflect common consumer practices. After the contact period, the solutions were transferred to dark glass bottles for subsequent analysis.
- **Photoinitiator, phthalate ester, and perfluorinated compound Analysis:** Sample preparation was conducted in accordance with European Union Regulation 10/2011.[19] Each sample was placed in a beaker and filled with 95% ethanol, which was then covered with aluminum foil and transferred to a preheated oven for controlled migration testing.

For phthalates, photoinitiators, and PFOA, migration conditions were set at 70 °C (±2 °C) for 2 h and 100 °C (±3 °C) for 2 h. Given the boiling point of ethanol (78.37 °C), an alternative migration condition was applied for these compounds, using 60 °C (±2 °C) for 3.5 h.

To conduct specific migration analysis of bisohenols, potoinitiators, phthalate esters and PFCs, ethanol and water simulants were directly injected into the LC-MS/MS system.[20]

LC-MS/MS instrumentation

The analyses were carried out using an Agilent 1260 Model Liquid Chromatography and 6460 Triple Quadrupole MS/MS Detector. Chromatographic separation was performed using an Infinity Lab Poroshell 120 EC-C18 column (2.7 µM;2.1 × 150mm) (Agilent Technologies, USA). The injection volume was 5 µl and column oven temperature was 40 °C. The mobile phases and gradient conditions were listed in Table S3.

Analyses of polymer type

A Nicolet 6700 FTIR spectrometer (Thermo Nicolet Corp., Madison, WI) in attenuated total reflectance (ATR) mode over the frequency range of 7400–350 cm^{-1} was used for identification of type of polymer type in cups. The spectra were obtained at a resolution of 0.5 cm^{-1}. The sample spectra were identified by comparing data in such IR libraries (Know It All Informatics System, IR edition v. 7.9 and HaveItAll® IR databases, all from Bio-Rad Laboratories, Inc). The ATR–FTIR spectra obtained from the investigated cups confirmed the presence of polyethylene (PE) and polystyrene (PS) as the main polymer types. The PE spectrum showed characteristic bands at approximately 2915 and 2848 cm^{-1} corresponding to C–H stretching vibrations and ~1470–1460 cm^{-1} associated with CH_2 bending vibrations. In contrast, the PS spectrum exhibited typical aromatic bands at ~1600 cm^{-1} (C=C stretching), ~1490 cm^{-1}, and ~760–700 cm^{-1} related to aromatic C–H out-of-plane bending vibrations. The infrared spectra of the polyethylene (PE) and polystyrene (PS) are shown in Figures 1 and 2.

Method validation

The method validation data are presented in Table S4. For bisphenols, critical parameters such as the limit of detection (LOD), limit of quantification (LOQ), linearity, precision, and recovery were assessed in line with JRC guidelines.[21] Validation was performed at low, medium, and high concentration levels using vegetable oil and beverage matrices. Recovery rates (0.01–0.1 mg/kg, $n = 6$) exhibited correlation coefficients exceeding 0.995, with six calibration levels (0.005–0.1 mg/kg). Photoinitiator validation[22] encompassed five distinct matrices, including fruit juice and butter, achieving correlation coefficients above 0.99. Calibration standards (0.005–0.1 mg/kg) and precision tests confirmed acceptable accuracy (70–120%) and reproducibility (RSD ≤20%). For phthalate esters, validation involved vegetable oil, 3% acetic acid, and 10% ethanol matrices, yielding recoveries of 85–100%, LODs of 1.4–2.5 µg/kg, LOQs of 3.2–5 µg/kg, and RSD values below 10%, demonstrating robust precision. PFOA-PFOS analyses, adhering to

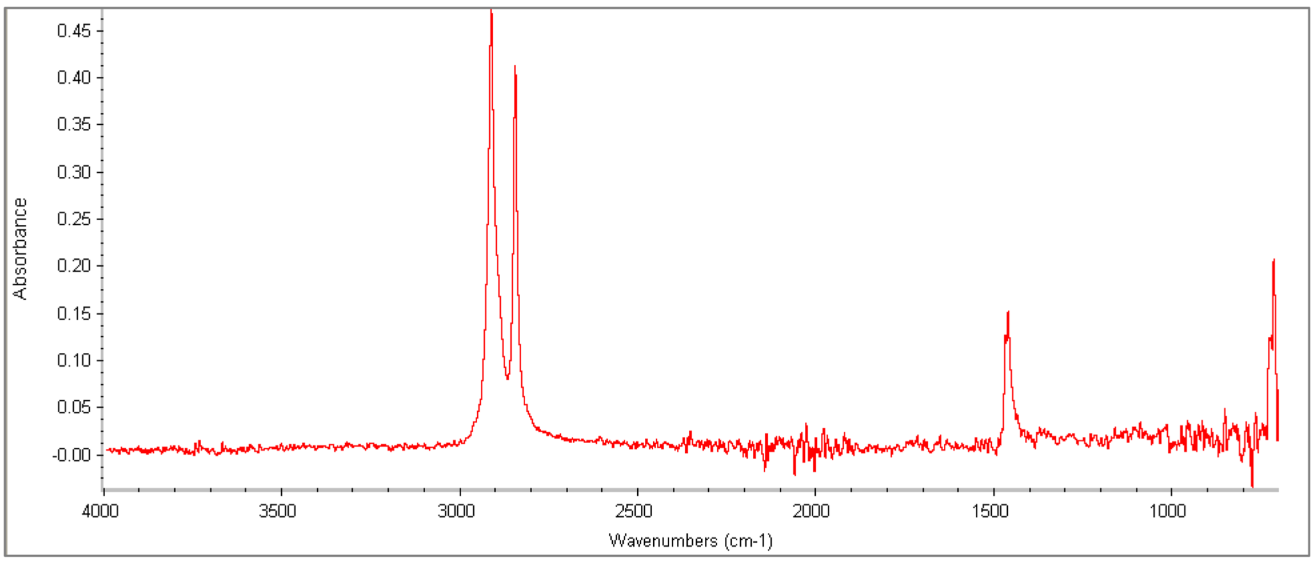

Figure 1. Infrared spectra of the polyethylene (PE).

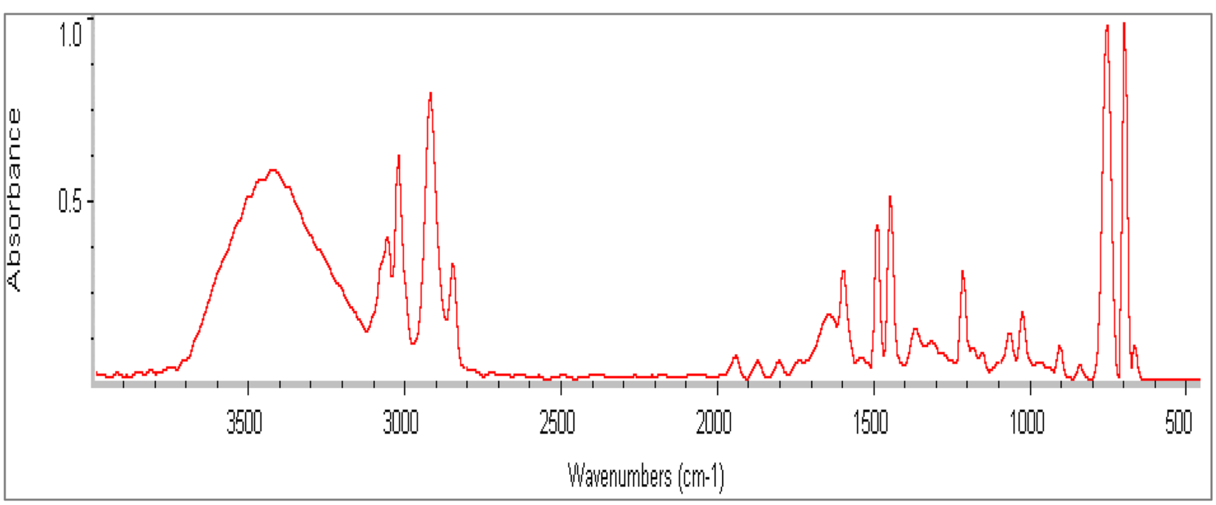

Figure 2. Infrared spectra of the polystyrene (PS).

rigorous validation protocols, employed food simulant D1 (50% ethanol). Calibration curves achieved correlation coefficients exceeding 0.995, supported by internal standard calibration. Recovery rates surpassed 70%, with reproducibility metrics (RSD: 3–8%) and inter-laboratory precision meeting stringent international standards. Matrix effects were effectively mitigated through strategic selection of validation matrices. These comprehensive validations confirm the reliability, accuracy, and reproducibility of the analytical methods, aligning with global regulatory benchmarks and ensuring high-quality analytical performance across diverse sample matrices.

Statistical analysis

Statistical analyses were performed using 2025 software OriginPro (version 2025 for Windows, OriginLab Corporation, Northampton, MA, USA). The mean values phthalate and photoinitiator concentrations were employed to characterize the transfer of these mentioned contaminants to cups. Data normality was first assessed using the Shapiro–Wilk test. Due to the presence of non-parametric data for variables including phthalate and photoinitiator, Spearman's correlation test was chosen to evaluate phthalate and photoinitiator present in various cup samples, heatmaps were produced using OriginPro (version 2025 for Windows, OriginLab Corporation, Northampton, MA, USA). Significance was assumed when $P < 0.05$.

Results and discussion

Chemical compounds disruptions according to cup types

Disposable hot drink cups are primarily composed of paper (90–95% by weight) and are typically laminated with polyethylene (5–10% by weight) to prevent liquid leakage and provide thermal insulation.[14] Given their widespread use, the potential migration of chemical additives from these materials into beverages warrants serious attention. This study systematically investigated the migration of phthalates, bisphenols, photoinitiators (PIs), and perfluorinated compounds (PFCs) from different types of disposable cups (Figures 3 and 4).

The concentrations of detected chemical compounds in polyethylene (PE) and polystyrene (PS) based cups (Figures 1 and 2) are presented in Figure 3. The highest total chemical contamination was observed in kraft paper cups (E1, E2, E3), where the cumulative concentrations exceeded 1.4 mg/kg. Among the detected contaminants, di-(2-ethylhexyl) phthalate (DEHP) was the most abundant, followed by benzophenone (BP). Additionally, diisobutyl phthalate (DIBP), diisodecyl phthalate (DIDP), bisphenol A (BPA), bisphenol S (BPS), perfluorooctanoic acid (PFOA), BP, 1-hydroxycyclohexyl phenyl ketone (HCPK), 4-methyl benzophenone (4-MBP), 4-hydroxybenzophenone (4HBP), and ethyl 4-dimethylaminobenzoate (EDMAP) were detected at varying concentrations.

The second highest total chemical burden was found in printed paper cups (C6, C7, C11, C17, C18, C19, C20), where the cumulative concentrations exceeded 0.5 mg/kg. In these samples, DBP, DIBP, DEHP, BP, and HCPK were detected. The concentration of DEHP ranged from 0.02 to 0.43 mg/kg, while BP and HCPK ranged from 0.01 to 0.05 mg/kg. In colored paper cups, multiple phthalates (DBP, DIBP, DEHP, BBP, DINP, DIDP), bisphenols (BPA, BPS), and photoinitiators (BP) were also detected. In contrast, no detectable contaminants were found in unprinted foam and plastic cups, suggesting that printing and color additives contribute significantly to chemical migration.

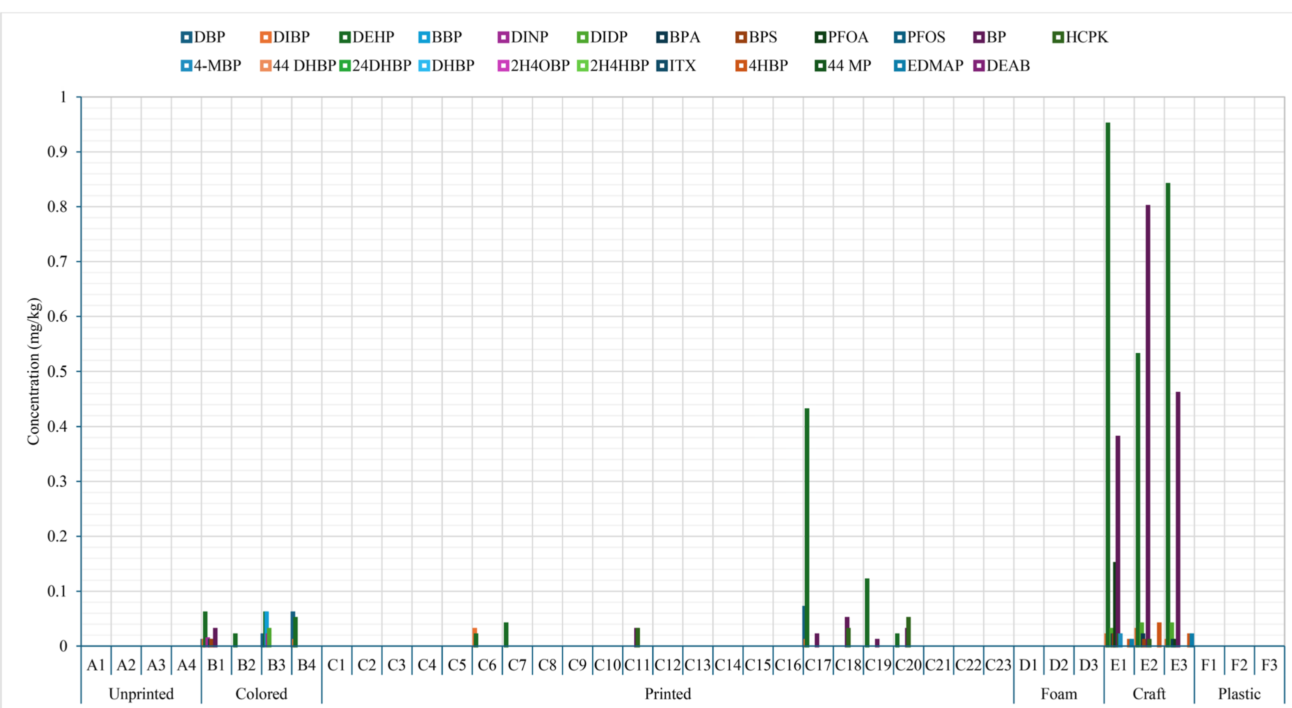

Figure 3. Chemical compound concentrations in cup samples.

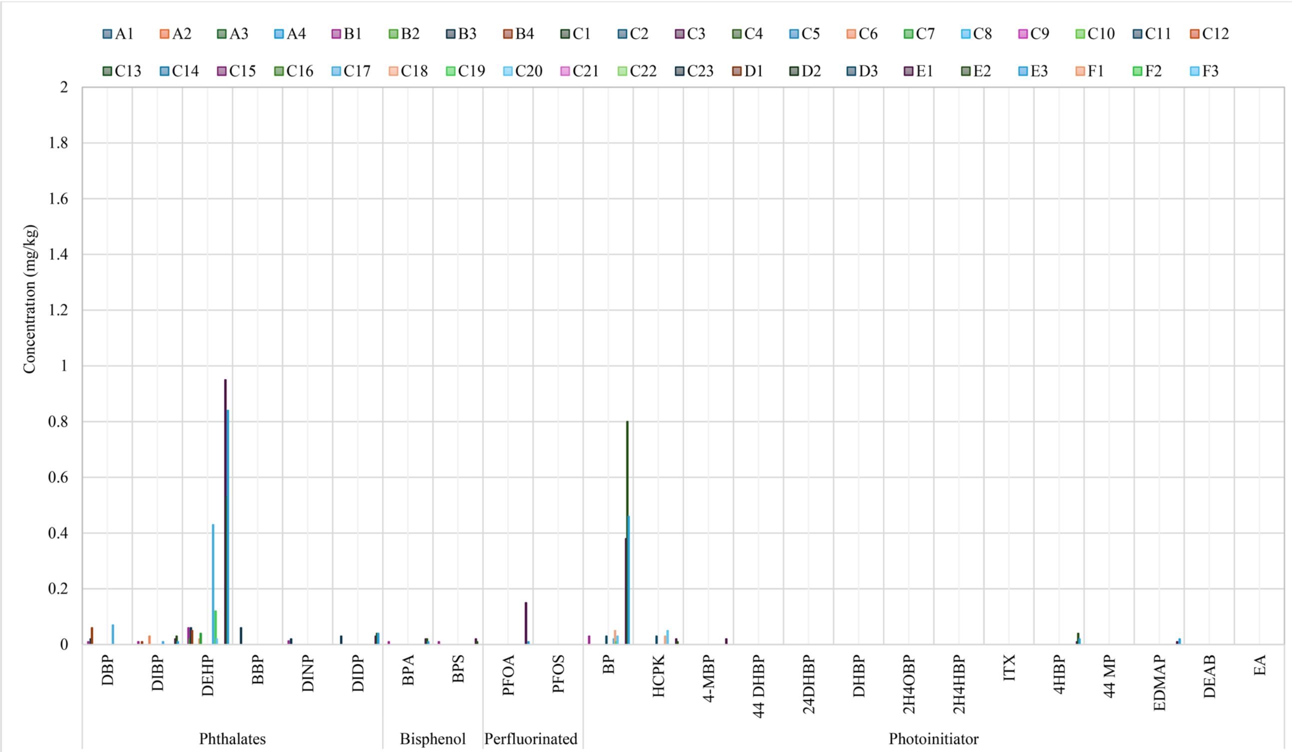

Figure 4. The profile of chemical group proportion of compound concentrations in cup samples.

Limited studies have reported the occurrence of hazardous contaminants in disposable cups.[9,23] analyzed 14 paper cups in Jeddah, Saudi Arabia, for metal ion migration into hot beverages. Their findings revealed the presence of vanadium, chromium, copper, cobalt, and arsenic at concentrations ranging from 0.04 to 1.80 µg/L, as well as nitrate, nitrite, chloride, bromate, fluoride, and sulfate ions at levels between 0.003 and 49.21 mg/L. Although these concentrations were below the World Health Organization (WHO) permissible limits for drinking water, the presence of vanadium (1.24 µg/L) and fluoride ions (1.03 mg/L) raised concerns regarding potential health risks from long-term bioaccumulation.

Similarly, seven phthalates DBP, BBP, DEHA, DEHP, DNOP, DINP, and DIDP in paper cups using gas chromatography–mass spectrometry (GC-MS) was detected.[9] Their study also assessed the migration potential of these phthalates under different conditions. The reported migration levels were 0.07–3.14 mg/kg for DBP, 0.16–42.69 mg/kg for DEHA, 0.45–58.56 mg/kg for DEHP, and 0.3–2.4 mg/kg for DNOP, demonstrating a significant risk of consumer exposure through daily use.[6]

Paper-based beverage cups typically present a multilayer structure, where the paper/board is combined with a polymer coating layer to provide functionality and barrier performance.[4] In multilayer food contact materials, the migration of substances is generally governed by diffusion and mass transfer through the different layers, meaning that substances originating from the paper/board phase may need to pass through the polymer coating before reaching the beverage. Furthermore, the presence of a functional barrier layer can reduce material transfer under normal or foreseeable conditions of use, although such barrier efficiency depends on the system and conditions.[24] In addition, stacked storage of cups can lead to set-off migration, where compounds from the outer printed surface may transfer to the inner food-contact side, potentially bypassing the intended multilayer barrier effect.[25]

This study highlight the potential health risks associated with the use of disposable beverage cups due to the migration of hazardous chemicals, particularly phthalates, bisphenols, and photoinitiators. The high concentrations detected in craft and printed cups emphasize the need for stricter regulations on the manufacturing and printing processes of food-contact materials. Considering the widespread consumption of disposable cups, further studies on long-term human exposure and risk assessment models are crucial for developing effective mitigation strategies.

Although the present study provides important insights into the occurrence and migration of selected chemical contaminants from beverage cups, several limitations should be acknowledged. The investigation focused exclusively on specific cup types and targeted analytes and therefore did not account for the broader spectrum of potential chemical migrants or the influence of confounding factors and real-world variability. Within these constraints, the measured migration levels of six phthalates, two bisphenols, two perfluorinated compounds (PFCs), and fourteen photoinitiators indicate that certain beverage cups may represent a potential source of consumer exposure. However, without comprehensive exposure modeling and risk characterization, the magnitude and public health significance of this potential risk cannot be definitively established. Further studies incorporating realistic usage scenarios and cumulative exposure assessment are warranted to more accurately evaluate the associated health implications.

Chemical compounds disruptions in cup samples

This study investigated the migration of six phthalates, two bisphenols, two perfluorinated compounds (PFCs), and fourteen photoinitiators from disposable cups into beverages. The findings provide critical insights into the potential contamination risks posed by these materials.

Phthalate concentrations in disposable cup samples collected in Turkey were analyzed, and their distribution is presented in Figure 4. The most dominant phthalate detected was di-(2-ethylhexyl) phthalate (DEHP), particularly in colored, printed, and craft cups, with concentrations ranging from 0.02 to 0.95 mg/kg (C6 and E1). Diisobutyl phthalate (DIBP) was the second most dominant phthalate, with concentrations ranging from 0.01 to 0.03 mg/kg (B1, B4, C17, E3, C6, and E2). Dibutyl phthalate (DBP) and diisodecyl phthalate (DIDP) were detected in four samples, while benzyl butyl phthalate (BBP) was identified only in B3 at 0.06 mg/kg.

Our findings align with previous studies.[26,27] DEHP and DIDP were the most frequently detected phthalates in cardboard food packaging, with pizza boxes showing DEHP concentrations up to 10 μg/g was reported.[26] Similarly, DEHP levels in paperboard food-contact materials ranging from 0.97 mg/kg to 66.3 mg/kg was detected.[27] These findings indicate that disposable paper-based food packaging, including cups, represents a significant source of phthalate exposure, potentially posing health risks due to their endocrine-disrupting properties. Among the phthalates detected, seven samples exceeded the SML for diisobutyl phthalate (DIBP) (0.01 mg/kg), as stipulated by EU Regulation No. 10/2011.[19] Additionally, di(2-ethylhexyl) phthalate (DEHP) concentrations in three samples surpassed the EU's SML of 0.6 mg/kg and the German Federal Institute for Risk Assessment (BfR) limit of 0.3 mg/kg.[28] Other detected phthalates, including dibutyl phthalate (DBP), benzyl butyl phthalate (BBP), diisononyl phthalate (DINP), and diisodecyl phthalate (DIDP), were within the permissible limits. These findings highlight the urgent need for stricter regulatory enforcement and alternative material choices in disposable food packaging.

Two bisphenols, bisphenol A (BPA) and bisphenol S (BPS) were detected in the samples. Compared to phthalates and photoinitiators, bisphenol concentrations were relatively lower. BPA was the predominant bisphenol, with concentrations ranging from 0.01 to 0.02 mg/kg (B1, B3, B4, E1, E2, and E3). BPS was detected in B1, E1, and E2, at 0.01–0.02 mg/kg. Despite extensive research on bisphenol contamination in food packaging[10,29–33] few studies have specifically focused on bisphenol migration from disposable paper cups.[14] This study highlights the need for further investigation into bisphenol leaching from these materials and its potential implications for human health. Bisphenols, particularly bisphenol A (BPA) and bisphenol S (BPS), were detected in this study, but all concentrations were below regulatory limits. The EU and BfR have set an SML of 0.05 mg/kg for BPA and BPS in varnishes and coatings.[28,34] However, despite compliance, regulatory agencies have imposed bans on BPA in certain food-contact applications due to its endocrine-disrupting effects and links to metabolic disorders.[34,35] While our findings indicate no immediate regulatory violations for bisphenols, the complete ban on BPA in some food-contact materials suggests that even low-level exposure should be a cause for concern. Future research should explore the potential cumulative effects of low-dose bisphenol exposure from multiple food-packaging sources.

Perfluorinated compounds (PFCs) are widely used in food-contact materials due to their chemical stability, hydrophobicity, and resistance to high temperatures.[36] Their presence in disposable cups raises concerns about long-term exposure and environmental persistence. This study detected perfluorooctanoic acid (PFOA) in all craft cup samples (E1, E2, and E3) at 0.15 mg/kg, <LOQ, and 0.01 mg/kg, respectively. Perfluorooctanesulfonic acid (PFOS) was below the limit of quantification (LOQ) in E2 and undetected in all other samples. In 13 of 35 food-contact materials from the Norwegian market, including paper cups, PFCs was detected where ΣPFC concentrations reached 0.021 μg/kg.[37] Given the persistence and bioaccumulative nature of PFCs, these findings highlight the importance of strict monitoring and regulatory control over their use in disposable beverage containers.

Photoinitiators, commonly used in UV-cured inks and coatings, are known to migrate from printed packaging materials into food and beverages. This study analyzed 14 photoinitiators, identifying benzophenone (BP) as the most abundant, making it the second most prevalent chemical contaminant overall. BP concentrations ranged from 0.01 to 0.8 mg/kg (C19 and E2). 1-Hydroxycyclohexyl phenyl ketone (HCPK) was detected in six samples, with concentrations of 0.01–0.05 mg/kg (E2, E1, C11, C18, and C20). 4-Hydroxybenzo phenone (4-HBP) was present in E1, E2, and E3 at 0.01–0.04 mg/kg, while ethyl 4-dimethylaminobenzoate (EDMAP) was found in E1 and E3 at 0.01–0.02 mg/kg. Notably, 10 of the 14 photoinitiators analyzed were undetected in all cup samples. Despite limited research on photoinitiator migration from paper-based food-contact materials was studied[38,39] and they confirm that BP and HCPK are common contaminants in food packaging. BP and HCPK was detected in Belgian straws, boxes, and trays, with BP levels up to 0.006 mg/kg and HCPK up to 0.021 mg/kg.[38] BP concentrations were identified in packaging materials from Spain.[25] Our findings further reinforce the role of paper cups as a potential source of photoinitiator exposure, necessitating further investigation.

The presence of photoinitiators in excess of regulatory limits is particularly concerning because these compounds can migrate from packaging materials into food and beverages, posing risks of genotoxicity.[39] Perfluorinated compounds, widely used for their hydrophobic and grease-resistant properties, are a growing global health concern due to their persistence and bioaccumulative nature.[40] Our study detected perfluorooctanoic acid (PFOA) at levels exceeding the EU's SML of 0.01 mg/kg in two samples, highlighting potential regulatory noncompliance. The detection of PFOA above regulatory thresholds in paper cups underscores the necessity for industry-wide phase-outs and the adoption of safer alternatives.

The observed migration behavior can be explained based on physicochemical and mass transfer principles. The migration behavior observed in multilayer paper cups is dominated by the diffusional mechanism in the food contact material. Temperature-dependent molecular mobility is a critical factor in migration behavior. Compounds with lower

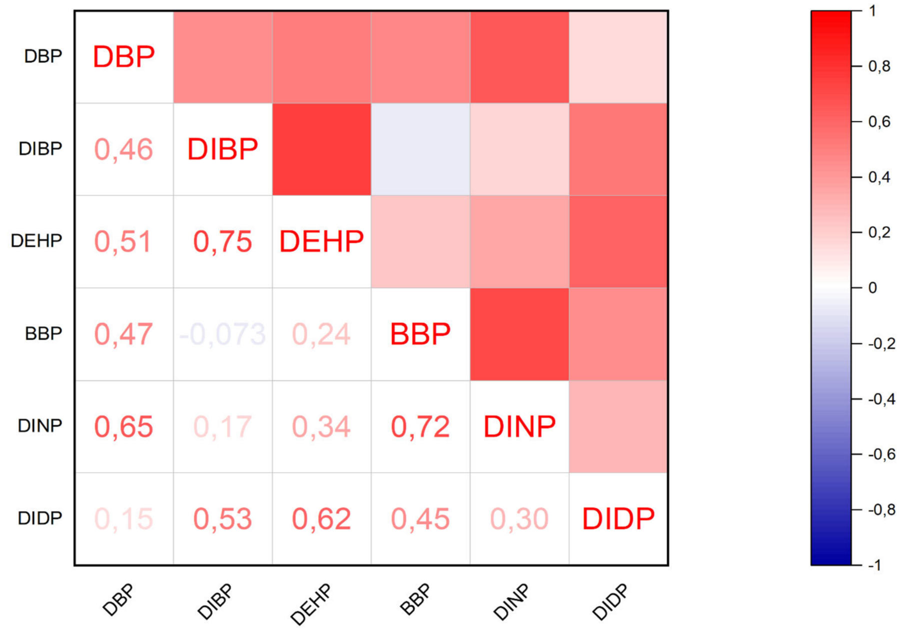

Figure 5. Spearman correlation analysis of phthalate concentrations in cups.

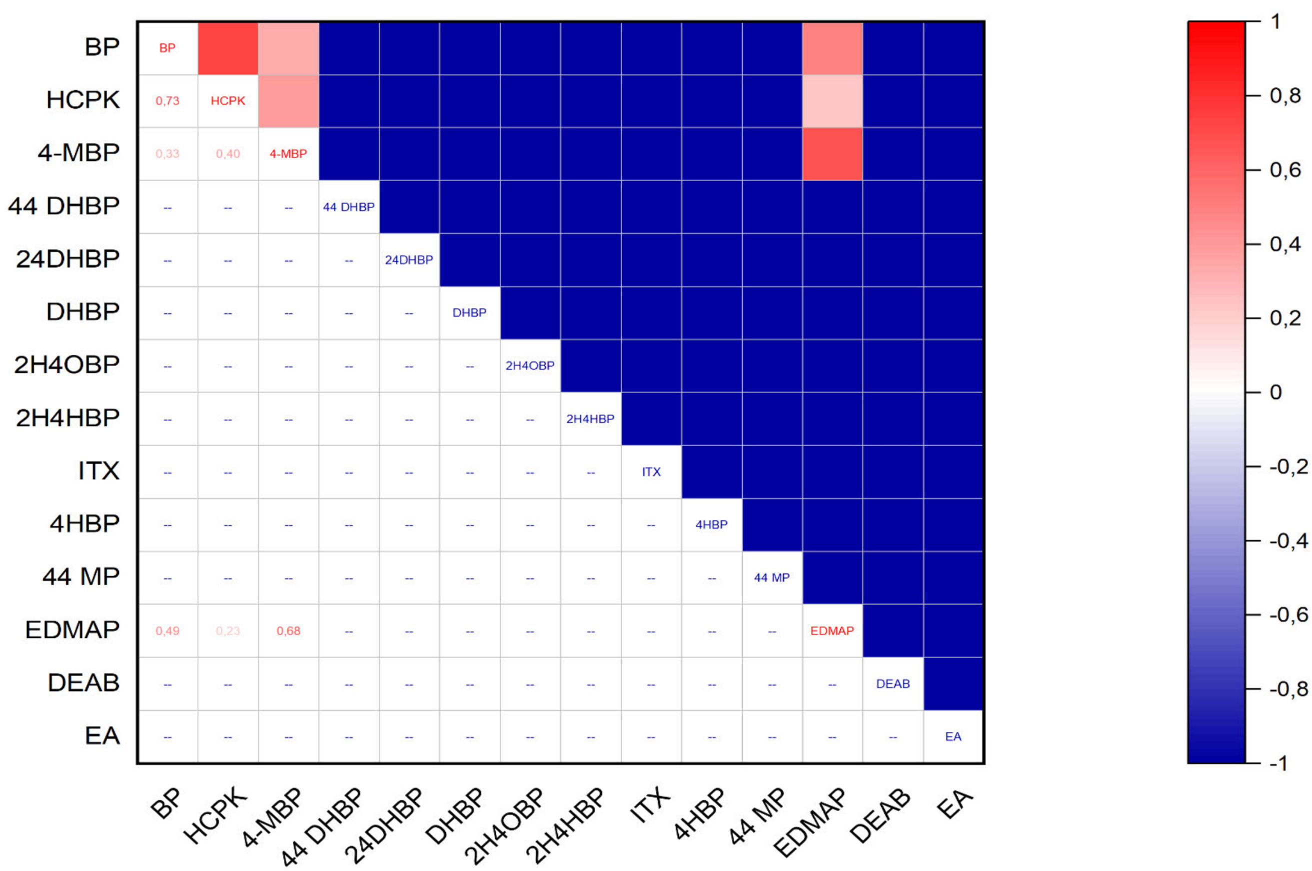

Figure 6. Spearman correlation analysis of photoinitiator concentrations in cups.

molecular weight and higher volatility are expected to migrate more easily due to higher rates of diffusion in the polymer material. Additionally, the partitioning effect between the polymer material and the simulant is also a factor in the migration behavior. Compounds with a higher affinity for the simulant are expected to be present in higher concentrations. The higher contaminant concentrations observed in craft and printed cups could be related to the presence of additional contaminants such as printing inks and coatings, in accordance with the observed diffusion-controlled migration behavior in multilayer food contact materials.

Ensuring food safety and public health requires stringent regulations on food contact materials. Many countries, particularly developed nations, have implemented comprehensive legal frameworks to limit contaminants that pose health risks. Among these, the European Union (EU) and United States (US) regulations are the most widely referenced worldwide.[41] A comparison of the contaminants identified in this study with established legal limits is presented in Table S5. Our findings reveal that several samples exceeded the specific migration limits (SMLs) set by international regulations, particularly for phthalates, photoinitiators, and perfluorinated compounds (PFCs).

Spearman's correlation analysis was conducted to assess the relationships between contaminant levels in the cup samples (Figures 5 and 6). Among phthalates, DEHP showed the strongest positive correlation with DIBP ($r = 0.75$, $P < 0.01$), indicating a potential co-occurrence or shared contamination source. Similarly, DINP exhibited a significant correlation with BBP ($r = 0.72$, $P < 0.01$), suggesting that these compounds may originate from similar raw materials or processing conditions. For photoinitiators, BP showed the highest positive correlation with HCPK ($r = 0.73$, $P < 0.01$), supporting previous findings that these compounds frequently migrate together from printed coatings. These correlations highlight the importance of identifying contamination sources and implementing stricter manufacturing controls to mitigate consumer exposure.

Conclusion

In this study, migration levels of phthalates, bisphenols, photoinitiators (PIs), and two perfluorinated compounds (PFCs) were determined in beverage cups. Among the detected contaminants, di(2-ethylhexyl) phthalate (DEHP) was the predominant phthalate. Bisphenol A (BPA) was the most abundant bisphenol, while benzophenone (BP), 4-hydroxy benzophenone (4HBP), and hydroxycyclohexyl phenyl ketone (HCPK) were the most frequently detected photoinitiators. Additionally, two perfluorinated compounds (PFCs) was identified in two samples. Notably, craft and colored paper cups exhibited the highest levels of these contaminants, suggesting that printing, coatings, and material composition significantly influence chemical migration. Future research should focus on long-term exposure risks, cumulative effects of multiple contaminants, and the efficacy of alternative food-packaging solutions to mitigate human health risks.

Author contribution

CRediT: **Sezer Kıralan**: Final manuscript check, contribution to the design of the work, improving text quality; **Isra Toptancı:** sample preparation and performing analyses; **Cansu Sezer**: Formal analysis, Investigation.

Disclosure statement

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

Data availability statement

The datasets generated and/or analyzed in the current study are available from the corresponding author upon reasonable request.

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Cansu Sezer http://orcid.org/0000-0003-1522-064X

References

[1] Zhou, Y.; Chen, M.; Zhao, F.; Mu, D.; Zhang, Z.; Hu, J. Ubiquitous Occurrence of Chlorinated Byproducts of Bisphenol A and Nonylphenol in Bleached Food Contacting Papers and Their İmplications for Human Exposure. *Environ. Sci. Technol.* 2015, *49*, 7218–7226. DOI: 10.1021/acs.est.5b00831.

[2] Ranjan, V. P.; Joseph, A.; Goel, S. Microplastics and Other Harmful Substances Released from Disposable Paper Cups into Hot Water. *J. Hazard. Mater.* 2021, *404*, 124118. DOI: 10.1016/j.jhazmat.2020.124118.

[3] Foteinis, S. How Small Daily Choices Play a Huge Role in Climate Change: The Disposable Paper Cup Environmental Ban. *J. Cleaner Prod.* 2020, *255*, 120294. DOI: 10.1016/j.jclepro.2020.120294.

[4] Dixon, J. 2011. *Multilayer Packaging for Food and Beverages (Packaging Materials: 9)*; ILSI Europe: Brussels.

[5] Tsochatzis, E. D. Food Contact Materials: Migration and Analysis. challenges and Limitations on İdentification and Quantification. *Molecules* 2021, *26*, 3232. DOI: 10.3390/molecules26113232.

[6] Kato, L. S.; Conte-Junior, C. A. Safety of Plastic Food Packaging: The Challenges about Non-İntentionally Added Substances (NIAS) Discovery, İdentification and Risk Assessment. *Polymers* 2021, *13*, 2077. DOI: 10.3390/polym13132077.

[7] Chen, Q.; Peng, C.; Xie, R.; Xu, H.; Su, Z.; Yilihan, G.; Wei, X.; Yang, S.; Shen, Y.; Ye, C.; Jiang, C. Placental and Fetal Enrichment of Microplastics from Disposable Paper Cups: İmplications for Metabolic and Reproductive Health during Pregnancy. *J. Hazard. Mater.* 2024, *478*, 135527. DOI: 10.1016/j.jhazmat.2024.135527.

[8] Lopez-Espinosa, M.-J.; Granada, A.; Araque, P.; Molina-Molina, J.-M.; Puertollano, M.-C.; Rivas, A.; Fernández, M.; Cerrillo, I.; Olea-Serrano, M.-F.; López, C.; Olea, N. Oestrogenicity of Paper and Cardboard Extracts Used as Food Containers. *Food Addit. Contam.* 2007, *24*, 95–102. DOI: 10.1080/02652030600936375.

[9] Park, Y. N.; Choi, M. S.; Rehman, S. U.; Gye, M. C.; Yoo, H. H. Simultaneous GC-MS Determination of Seven Phthalates in Total and Migrated Portions of Paper Cups. *Environ. Sci. Pollut. Res. Int.* 2016, *23*, 10270–10275. DOI: 10.1007/s11356-016-6604-6.

[10] Liao, C.; Kannan, K. Widespread Occurrence of Bisphenol A in Paper and Paper Products: İmplications for Human Exposure. *Environ. Sci. Technol.* 2011, *45*, 9372–9379. DOI: 10.1021/es202507f.
[11] Liu Wei, L. W.; Zhang Nan, Z. N.; Fan Sai, F. S.; Li Bing, L. B.; Tu RuiYing, T. R.; Zhao Rong, Z. R.; Wu GuoHua, W. G. 2016. Determination of the Migration of Photoinitiators from Paper Cup into Food Stimulants by Gas Chromatography-Tandem Mass Spectrometry. DOI: 10.5555/20163257187
[12] Joseph, A.; Parveen, N.; Ranjan, V. P.; Goel, S. Drinking Hot Beverages from Paper Cups: Lifetime İntake of Microplastics. *Chemosphere* 2023, *317*, 137844. DOI: 10.1016/j.chemosphere.2023.137844.
[13] Liu, G.; Wang, J.; Wang, M.; Ying, R.; Li, X.; Hu, Z.; Zhang, Y. Disposable Plastic Materials Release Microplastics and Harmful Substances in Hot Water. *Sci. Total Environ.* 2022, *818*, 151685. DOI: 10.1016/j.scitotenv.2021.151685.
[14] Tabakoglu, N.; Sezer, K.; Çelik, S. Microplastics and Endocrine-Disrupting Chemicals Released from Disposable Hot Beverage Cups and from Teabags, and Their Evaluation in Terms of Human Health Safety. *J. Elementol.* 2024, *29*, 245–263.
[15] Gómez-Hens, A.; Aguilar-Caballos, M. P. Social and Economic İnterest in the Control of Phthalic Acid Esters. *TrAC, Trends Anal. Chem.* 2003, *22*, 847–857. DOI: 10.1016/s0165-9936(03)01201-9.
[16] Liang, Q.; Wang, Z.; Du, W.; Liu, W.; Cao, J.; Ren, J.; Lian, W.; Lu, H.; Li, H. Determination of 18 Photoinitiators in Food Paper Packaging Materials by FastPrep-Based Extraction Combined with GC–MS. *Food Chem.* 2022, *377*, 131980. DOI: 10.1016/j.foodchem.2021.131980.
[17] Banaderakhshan, R.; Kemp, P.; Breul, L.; Steinbichl, P.; Hartmann, C.; Fürhacker, M. Bisphenol A and İts Alternatives in Austrian Thermal Paper Receipts, and the Migration from Reusable Plastic Drinking Bottles into Water and Artificial Saliva Using UHPLC-MS/MS. *Chemosphere* 2022, *286*, 131842. DOI: 10.1016/j.chemosphere.2021.131842.
[18] Priovolos, I.; Samanidou, V. Bisphenol A and İts Analogs Migrated from Contact Materials into Food and Beverages: An Updated Review in Sample Preparation Approaches. *J. Sep. Sci.* 2023, *46*, e2300081. DOI: 10.1002/jssc.202300081.
[19] EC. European Commission Regulation (EU) No 10/2011 of 14 January 2011 on Plas-Tic Materials and Articles İntended to Come into Contact with Food. *Off. J. Eur. Union* 2011, *12*, 1–89.
[20] Ierapetritis, I.; Lioupis, A.; Lampi, E. Determination of Phthalates into Vegetable Oils by İsotopic Dilution Gas Chromatography Mass Spectrometry. *Food Anal. Methods* 2014, *7*, 1451–1457. DOI: 10.1007/s12161-013-9770-x.
[21] EUR 24105. 2009 *EN-1st Edition Guidelines for Performance Criteria and Validation Procedures for Analytical Methods Used in Controls of Food Contact Materials*; JRC Scientifc and Technical Reports: Italy.
[22] Gallart-Ayala, H.; Núñez, O.; Moyano, E.; Galceran, M. T. Analysis of UV İnk Photoinitiators in Packaged Food by Fast Liquid Chromatography at Sub-Ambient Temperature Coupled to Tandem Mass Spectrometry. *J. Chromatogr. A* 2011, *1218*, 459–466. DOI: 10.1016/j.chroma.2010.11.054.
[23] Akhdhar, A.; El-Hady, D. A.; Almutairi, M.; Alnabati, K. K.; Alowaifeer, A.; Alhayyani, S.; Albishri, H. M.; Al-Bogami, A. S. Rapid Release of Heavy Metals and Anions from Polyethylene Laminated Paper Cups into Hot Water. *Environ. Chem. Lett.* 2022, *20*, 35–40. DOI: 10.1007/s10311-021-01315-7.
[24] Aurela, B. Migration of Substances from Paper and Board Food Packaging Materials. Doctoral Dissertation, University of Helsinki, 2001.
[25] Asensio, E.; Peiro, T.; Nerín, C. Determination the Set-off Migration of İnk in Cardboard-Cups Used in Coffee Vending Machines. *Food Chem. Toxicol.* 2019, *130*, 61–67. DOI: 10.1016/j.fct.2019.05.022.
[26] Carlos, K. S.; de Jager, L. S.; Begley, T. H. Determination of Phthalate Concentrations in Paper-Based Fast Food Packaging Available on the U.S. market. *Food Addit. Contam. A Chem. Anal. Control. Expo. Risk Assess.* 2021, *38*, 501–512. DOI: 10.1080/19440049.2020.1859623.
[27] Suciu, N. A.; Tiberto, F.; Vasileiadis, S.; Lamastra, L.; Trevisan, M. Recycled Paper–Paperboard for Food Contact Materials: Contaminants Suspected and Migration into Foods and Food Simulant. *Food Chem.* 2013, *141*, 4146–4151. DOI: 10.1016/j.foodchem.2013.07.014.
[28] Anonymous. 2024. *BfR XXXVI. Paper and Board for Food Contact*. German Federal Institute for Risk Assessment: Germany.
[29] Wang, X.; Nag, R.; Brunton, N.; Siddique, M.; Harrison, S.; Monahan, F.; Cummins, E. A Probabilistic Approach to Model Bisphenol A (BPA) Migration from Packaging to Meat Products. *Sci. Total Environ.* 2023, *854*, 158815. DOI: 10.1016/j.scitotenv.2022.158815.
[30] Almeida Soares, D.; Pereira, I.; Sousa, J.; Bernardo, R.; Simas, R.; Vaz, B.; Chaves, A. Bisphenol Determination in UHT Milk and Packaging by Paper Spray İonization Mass Spectrometry. *Food Chem.* 2023, *400*, 134014.
[31] Dehdashti, B.; Nikaeen, M.; Amin, M. M.; Mohammadi, F. Health Risk Assessment of Exposure to Bisphenol A in Polymeric Baby Bottles. *Environ. Health Insights.* 2023, *17*, 11786302231151531. DOI: 10.1177/11786302231151531.
[32] Baz, L.; Alharbi, A.; Al-Zahrani, M.; Alkhabbaz, S.; Alsousou, R.; Aljawadri, H. The Effect of Different Storage Conditions on the Levels of Bisphenol A in Bottled Drinking Water in Jeddah City. *Adv. Public Health* 2023, *2023*, 1–6. DOI: 10.1155/2023/8278428.
[33] Kumar, A.; Singh, D.; Bhandari, R.; Malik, A.; Kaur, S.; Singh, B. Bisphenol A in Canned Soft Drinks, Plastic-Bottled Water, and Household Water Tank from Punjab. *J. Hazard. Mater. Adv.* 2023, *9*, 100205. DOI: 10.1016/j.hazadv.2022.100205.
[34] EC. Commission Regulation (EU) 2018/213 of 12 February 2018 on the Use of Bisphenol A in Varnishes and Coatings İntended to Come into Contact with Food and Amending Regulation (EU) No 10/2011 as Regards the Use of That Substance in Plastic Food Contact Materials. *Off. J. Eur. Union* 2018, *41*, 6–12.
[35] EC. Regulation (EU) No 609/2013 of the European Parliament and of the Council of. 12 June 2013 on Food İntended for İnfants and Young Children, Food for Special Medical. Purposes, and Total Diet Replacement for Weight Control and Repealing Council Directive. 92/52/EEC, Commission Directives 96/8/EC, 1999/21/EC, 2006/125/EC and 2006/141/EC, Directive 2009/39/EC of the European Parliament and of the Council and Commission Regulations (EC) No 41/2009 and (EC) No 953/2009. *Off. J. Eur. Union* 2013, *181*, 35–56.
[36] Ramírez Carnero, A.; Lestido-Cardama, A.; Vazquez Loureiro, P.; Barbosa-Pereira, L.; de Quir′os, A.; Send.; On, R. Presence of Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) in Food Contact Materials (FCM) and İts Migration to Food. *Foods* 2021, *10*, 1443. ′ DOI: 10.3390/foods10071443.
[37] Granby, K.; Tesdal Håland, J. *Per-and Polyfluorinated Alkyl Substances (PFAS) in Paper and Board Food Contact Materials-Selected Samples from the Norwegian Market 2017*; Report of Technical University of Denmark: Denmark, 2018.
[38] Di Mario, M.; Bauwens, G.; Peltier, F.; Goscinny, S.; Focant, J. F.; Purcaro, G.; Van Hoeck, E. Investigation of Potential Migratables from Paper and Board Food Contact Materials. *Front. Chem.* 2023, *11*, 1322811. DOI: 10.3389/fchem.2023.1322811.
[39] Zeng, B.; Cai, Z.; Lalevée, J.; Yang, Q.; Lai, H.; Xiao, P.; Liu, J.; Xing, F. Cytotoxic and Cytocompatible Comparison among Seven Photoinitiators-Triggered Polymers in Different Tissue Cells. *Toxicol. In Vitro.* 2021, *72*, 105103. DOI: 10.1016/j.tiv.2021.105103.
[40] Jala, A.; Adye, D. R.; Borkar, R. M. Occurrence and Risk Assessments of per-and Polyfluoroalkyl Substances in Tea Bags from India. *Food Control* 2023, *151*, 109812. DOI: 10.1016/j.foodcont.2023.109812.
[41] Ong, H. T.; Samsudin, H.; Soto-Valdez, H. Migration of Endocrine-Disrupting Chemicals into Food from Plastic Packaging Materials: An Overview of Chemical Risk Assessment, Techniques to Monitor Migration, and İnternational Regulations. *Crit. Rev. Food Sci. Nutr.* 2022, *62*, 957–979. DOI: 10.1080/10408398.2020.1830747.