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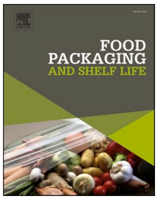

Beyond direct contact: Chemical migration from external printed components of tea packaging into infusions assessed by UPLC-IM-QTOF analysis

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ABSTRACT

The safety of food packaging has traditionally focused on materials in direct contact with food, often neglecting the potential contribution of printed external components. This study investigates the migration of chemical substances from non-food-contact elements of tea bag packaging—such as printed labels and external wrappers—into tea infusions prepared under realistic conditions. Migration was simulated by immersing both tea bags and their associated printed materials in boiling water. Extracts were analyzed using ultra-performance liquid chromatography coupled with ion mobility–quadrupole time-of-flight mass spectrometry (UPLC-IM-QTOF), enabling sensitive and multidimensional profiling of known and unknown migrants. Concentrations of identified substances ranged from 5.7 to 369 ng/g, with compound-specific detection limits spanning 1.1–12.3 ng/g. Principal Component Analysis (PCA) revealed that ink and varnish formulations contributed significantly to the variation in migration profiles among brands, despite identical tea compositions. Compounds such as hexadecyl methacrylate and benzophenone were uniquely associated with specific packaging types, while ubiquitous substances like acetyl tributyl citrate and erucamide indicated common ink usage. Notably, several potential endocrine disruptors were detected, although all migration levels remained below current regulatory limits. These results emphasize the importance of including all packaging layers in safety assessments and demonstrate the utility of UPLC-IM-QTOF for comprehensive non-targeted migration analysis.

1. Introduction

In recent years, increasing attention has been directed towards the chemical safety of food packaging materials, particularly with respect to the potential migration of substances from packaging into food and beverages. Regulatory frameworks such as the European Union's Regulation (EU) No 10/2011 (Commission Regulation EU, 2011) and national ordinances mandate strict evaluation of materials that come into direct contact with food. However, less emphasis has traditionally been placed on components of packaging that are not in direct contact with the consumable product—such as external wrappers, labels, and printed surfaces—despite mounting evidence that these components can still contribute to overall chemical migration. This blind spot is particularly critical, as the non-food-contact layers (specifically printed labels and external wrappers) can act as an indirect source of contamination through set-off, vapor-phase transfer, or diffusion phenomena during storage or thermal preparation. Although these outer components are not regulated as strictly as direct food-contact materials, they frequently contain complex mixtures of inks, coating additives, plasticizers, and photoinitiators that were never intended to contact the beverage itself, yet may still reach the consumer through indirect pathways.

One such mechanism is set-off migration, a phenomenon where chemicals from printed outer surfaces transfer to the inner food-contact layers through physical contact during storage or packaging processes (Lemos et al., 2017). This transfer can also occur indirectly through vapor-phase diffusion or sublimation, especially in products exposed to heat or moisture during preparation, such as tea infusions. Inks, varnishes, plasticizers, and other additives used in printing and coating formulations may contain both intentionally added substances (IAS) and non-intentionally added substances (NIAS), some of which may raise toxicological concerns (Aurela & Soderhjelm, 2007; Pulina and Johnke, n.d.). Photoinitiators, antioxidants, and plasticizers commonly found in UV-curable inks and coatings have been reported in several studies to migrate into food from packaging materials (Papilloud & Baudraz, 2002;

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Luis Aparicio & Elizalde, 2015).

Tea bags present a particularly relevant case for studying indirect migration due to their complex multilayered packaging and their preparation involving high-temperature water infusion. Typically, a tea bag consists of multiple components including the sachet material, string, staple, tag, and often an outer envelope or carton—each potentially comprising different materials, adhesives, and coatings. This structural complexity increases the number of interfaces where chemical transfer could occur. While previous research has focused largely on the migration from tea bag materials or sachet films in direct contact with hot water (Shruti & Kutralam-Muniasamy, 2024), little is known about the contribution of external printed components—such as inked tags, wrappers, or carton board—to the chemical profile of the final beverage. These elements, although not directly immersed in water, may still leach substances during storage, through condensation, or via vapor-phase migration when exposed to steam and elevated temperatures during brewing. This gap in understanding poses a potential risk, as substances not originally intended for food contact—particularly those classified as non-authorized or unknown NIAS—may still reach the consumer through indirect pathways. Given the widespread global consumption of tea (Https://Es.Statista.Com/Estadisticas/1287689/Consumo-Mundial-de-Te/) and the frequent use of such packaging configurations, assessing the full migration potential of all associated packaging layers is essential for ensuring comprehensive consumer safety.

To accurately characterize and identify migrating compounds from such complex matrices, advanced analytical instrumentation is essential. In this study, ultraperformance liquid chromatography coupled with ion mobility-quadrupole time-of-flight mass spectrometry (UPLC-IM-QTOF) was employed, as its capability to integrate orthogonal identification parameters (collision cross section, accurate mass, and retention time) provides a substantially higher level of confidence in the annotation of both IAS and NIAS compared with conventional LC–MS approaches. This technique represents a powerful tool in non-targeted and semi-targeted screening of migration substances due to its high sensitivity, resolving power, and multidimensional separation capabilities. UPLC enables high-efficiency chromatographic separation with excellent resolution and throughput, especially beneficial for complex sample types such as migration extracts. Coupling UPLC with ion mobility spectrometry (IMS) introduces an additional dimension of separation based on the size, shape, and charge of ions, providing drift time information that aids in distinguishing isobaric or co-eluting species. When integrated with a quadrupole time-of-flight (QTOF) mass analyzer, this setup allows for precise mass measurement, structural elucidation through accurate fragment ion detection, and increased confidence in compound identification (Shruti & Kutralam-Muniasamy, 2024).

The key advantage of UPLC-IM-QTOF in the context of food contact material analysis lies in its ability to reduce matrix interferences, improve the identification of unknowns, and correlate precursor and fragment ions across both retention time and ion mobility dimensions. These features significantly enhance the robustness of non-targeted screening workflows, especially when paired with comprehensive databases that incorporate retention time, exact mass, and collision cross section (CCS) values (Canellas et al., 2019, 2015).

In this context, the present study combines the analytical power of UPLC-IM-QTOF with chemometric analysis (Principal Component Analysis) to evaluate the extent and nature of chemical migration from the non-food-contact components of tea bag packaging—specifically printed labels and external wrappers—under realistic brewing conditions. By investigating the migration behavior of substances potentially originating from inks, varnishes, and coated papers, this research highlights the importance of broadening the scope of safety assessments to include all components of the packaging system. Through a multidimensional analytical approach, the study offers new insights into the impact of external packaging materials on food safety and supports the development of more comprehensive regulatory and quality control strategies.

2. Materials and methods

2.1. Reagents and materials

Ethanol of high-performance liquid chromatography (HPLC) grade was supplied by Scharlau Chemie S.A (Sentmenat, Spain). Deionized water was obtained from a MilliporeMilli-QPLUS 185 system (Madrid, Spain)

The reagents hexadecyl methacrylate, tetradecyl methacrylate, acetyl tributyl citrate, benzophenone, caffeine, didodecyl 3,3′-thiodipropionate, tris(2-ethylhexyl) trimellitate, erucamide,n,n′-diphenyl-p-phenylenediamine, polypropylene glycol (ppg 5), bis(2-(2-butoxyethoxy)ethyl) phthalate, methyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate, methyl 9,10-dihydroxyoctadecanoate were purchased from Merck (spain).

Tea bags, labels and the external wrappers were acquired from three different suppliers. Characteristics are shown in Table 1.

2.2. Migration and extraction

Migration tests were conducted by pouring boiling water directly over the tea bag, replicating the typical use conditions as closely as possible. This approach was chosen to simulate realistic consumer exposure, where the tea bag is in direct contact with hot water during infusion. In addition to the inner tea bag, the outer packaging components—specifically the label and the external wrapper, both of which contain printed inks—were also subjected to the same extraction procedure. These components, using the complete amount of material contained in a single tea bag for each test, were individually immersed in 200 mL of boiling water for 30 min to assess a worst-case extraction simulating exaggerated indirect transfer routes (set-off, steam or condensation), thereby enabling the identification of compounds potentially migrating from the outer printed materials.

2.3. Ultra-high-pressure-liquid chromatography coupled to ion mobility-quadrupole time of flight analyzer (UPLC-IM-Q/TOF)

For the screening of migration extracts, an advanced analytical platform combining ultra-high-pressure liquid chromatography

Table 1
Samples studied, brand, type of infusion, ink color of the external wrapper, ink color of the label and name of the sample.

Brand	Type of infusion	Ink color of the external wrapper	Ink color of the label	Name
Hornimans	tea	Red, yellow and black	Red, yellow and black	H
	chamomile	Yellow and green	Yellow and white	HM
	mint pennyroyal	Green, yellow and black	Green, yellow and black	HPM
Pompadour	tea	Red and green	Green	P
	chamomile	Blue, yellow, white and red	Blue white and red	PPM
	mint pennyroyal	Green, black and red	Green and black	PPMTV
La Barraca	tea	Green	Green	LB
	chamomile	Blue, yellow, white and red	Blue white and red	LB DMB
	mint pennyroyal	Green, black and red	Green and black	LB TV
La tetería	tea	Red and green	Green	TTT
	chamomile	Blue, yellow, white and red	Blue white and red	TTV
	mint pennyroyal	Green, black and red	Green and black	TTMV

(UHPLC) with ion mobility separation and high-resolution mass spectrometry (IM-QTOF) was employed. Analyses were performed using a Waters Acquity™ UHPLC system coupled to a Vion® IMS-QTOF mass spectrometer via an electrospray ionization (ESI) source. The instrumentation was housed at Waters Corporation facilities in Manchester, UK.

Chromatographic separation was carried out on a BEH C18 column (2.1 × 100 mm, 1.7 µm particle size), maintained at 35 °C and operated at a flow rate of 0.3 mL/min. The mobile phase consisted of water (A) and methanol (B), both acidified with 0.1 % formic acid. A gradient elution program was applied, starting at 95 % A and linearly increasing to 100 % B over 13 min, followed by a 2-minute re-equilibration period. Injection volume was set at 5 µL.

The ESI source was operated in both positive and negative ion modes using a capillary voltage of 3.0 kV and a sampling cone voltage of 30 V under sensitivity mode. Source and desolvation temperatures were 120 °C and 500 °C, respectively, with desolvation gas delivered at 800 L/h. Mass spectra were acquired over a scan range of *m/z* 50–1000, with Leucine-Enkephalin ([M+H]+, *m/z* 556.2766) serving as the lock-mass for real-time mass correction.

Data were collected in high-definition MSE mode (HDMSE), a data-independent acquisition (DIA) approach that simultaneously captures low-energy (6 V) and high-energy (20–40 V ramp) fragmentation spectra. Argon and nitrogen were used as the collision and ion mobility gases, respectively. Ion mobility separation was performed with a gas flow rate of 25 mL/min, wave velocity of 250 m/s, and pulse height of 45 V. Instrument calibration for both *m/z* and collision cross section (CCS) values was conducted using the Major Mix calibration solution from Waters Corporation.

Data acquisition was performed at a rate of 10 Hz using UNIFI software (version 1.8), which was also used for data processing. Compound identification relied on a non-targeted screening strategy based on the Song et al. FCM database. Matching parameters included a retention time window of ±0.25 min, mass accuracy within 5 ppm, and a CCS tolerance of 5 %. Migration samples were analyzed without prior derivatization or concentration. To support quantification and method validation, pure reference standards were spiked into water to determine recovery rates, detection limits, and generate external calibration curves.

3. Results

3.1. Identification and quantification of migrants

The comprehensive sampling and migration and extraction methodology developed allowed for the evaluation of migration not only from the materials in direct contact with the beverage but also from non-food-contact components that could contribute indirectly through transfer of components coming from the label and the external wrapper (Fig. 1). The aim of the work was to determine which migrants from the tea bags come from inks, varnishes or paper in the label and the external wrapper due to the transference from these external parts of the packaging. It will be similar as the set-off procedure that occurs in many materials.

The migration extracts were analyzed using UPLC-IM-Q/TOF, a technique chosen for its ability to minimize interferences from complex sample matrices by aligning precursor and fragment ions across both retention time and ion mobility (drift time) dimensions.

Data from three replicates of each sample were collected and analyzed using Principal Component Analysis (PCA) to identify potential differences among the sample groups. The statistical software EZInfo, integrated with the UNIFI platform, enabled seamless bidirectional data transfer and supported an in-depth evaluation of the acquired analytical data.

The PCA result (Fig. 2) show that the samples labeled as P, H, and LBDMB are clearly differentiated from the rest of the sample set, indicating distinct migration behaviors. To contextualize these findings, it is important to consider the experimental design: sample H corresponds to the migration from a tea bag of a specific brand into boiling water, while HM and HPM are from the same brand and formulation but differ only in the ink used on the outer packaging that contains the tea bag. Similarly, LB represents a different brand, with LBDMB and LBTV being its variants that also differ solely in the ink on the external wrapper. The same structure applies to P (a different brand) and its variants PPM and PPMTV, as well as to TTM, TTMV, and TTT, which belong to yet another brand but share the same internal tea composition and differ only in the outer packaging ink.

The clear separation of certain samples—particularly P, H, and LBDMB—from their respective brand variants suggests that there are influential factors beyond the tea formulation itself and the primary packaging. Since the only experimental variable within each brand

Fig. 1. Structure of the tea bag, label and the external wrapper.

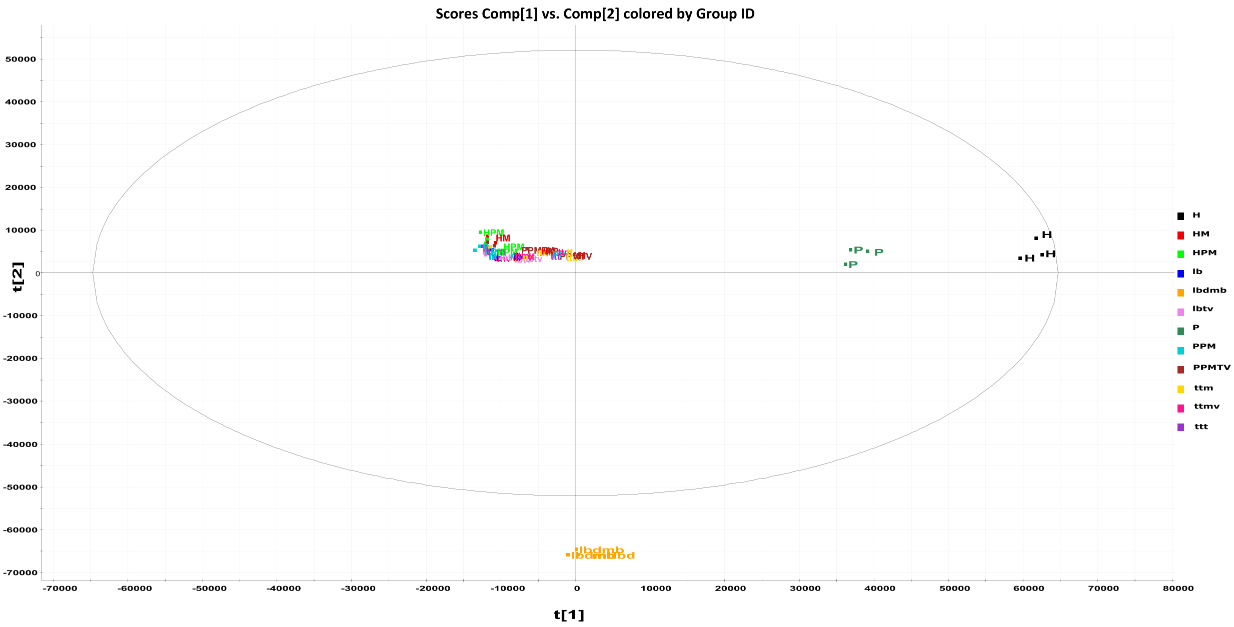

Fig. 2. Scores plot obtained from the Principal Component Analysis for the three replicates of each sample analyzed.

group is the type of ink or varnish used on the outermost packaging layer, the observed differences in migration profiles point to a potential role of the varnishes and inks in affecting the migration of substances from the tea bag into the hot water. This influence may be due to the chemical nature of them, their interaction with packaging materials, or possible leaching under high-temperature conditions.

These findings indicate that, even within the same brand and formulation, the external packaging—specifically, the varnish/ink composition—can significantly impact the migration behavior. This highlights the importance of evaluating not only the direct food-contact materials but also indirect components such as inks and external layers when assessing the safety and migration potential of food packaging systems. Further targeted studies are warranted to isolate and characterize the compounds responsible for these differences and to better understand the mechanisms driving ink-related migration.

The identified compounds were analyzed and compared across all the studied samples. For each sample, compounds detected in the printed packaging, the printed label, and those migrating into the tea from the tea bag were selected as candidates for studying potential set-off migration from inks to tea bags. This approach aimed to assess the transfer of substances from printed materials to the tea, providing insight into possible contamination risks and their implications for food safety.

The screening of the test samples was conducted using the extensive food contact materials (FCM) compound database developed by Song et al. (Song et al., 2022a, 2022b, 2022c). This comprehensive and continually evolving database contains over 10,000 entries, including both commonly used additives and non-intentionally added substances (NIAS) frequently found in FCMs. In addition to Collision Cross Section (CCS) values, the database provides critical analytical data such as retention times and accurate mass measurements, enhancing its utility for substance identification. The screening process was carried out using UNIFI software, which offers automated matching capabilities. By aligning the observed data—specifically retention time, exact mass, and CCS values—with the entries in the database, the software enables efficient and reliable compound identification within the acceptance criteria detailed in Section 2.3. To further ensure the reliability of identifications, selected compounds were confirmed using authentic reference standards, thereby strengthening the analytical confidence of the study. Table 2 shows the compounds identified, observed m/z, Mass error (mDa), collision cross section value (CCS), CCS delta %, retention time (RT), RT error, limit of detection (ng/g) (LOD). As observed, mass errors ranged from 0.0 to 0.7 mDa, CCS delta percentages from 0.0 % to 1.73 %, and retention time errors from 0.1 to 0.2 min. These values indicate a very good fit, considering the parameters outlined in Section 2.3.

Table 2
Name of the compound identified, observed m/z, Mass error (mDa), collision cross section value (CCS), CCS delta %, retention time (RT), RT error, limit of detection (ng/g) (LOD).

Name	Observed m/z	Mass error (mDa)	CCS	CCS delta %	RT	RT error	LOD (ng/g)
Hexadecyl methacrylate	311.2646	0.2	195.1	0.25	7.98	0.1	2.1
Tetradecyl Methacrylate	283.2633	0.2	186.5	0.88	7.91	0.2	1.3
Acetyl Tributyl Citrate	425.2143	−0.3	201.0	−1.47	7.35	0.2	3.5
Benzophenone	183.0804	0.0	136.48	0.90	5.82	0.2	2.6
Caffeine	195.0873	−0.4	135.4	−1.44	3.05	0.1	3.6
Didodecyl 3,3′-Thiodipropionate	515.4129	0.0	259.66	−0.8	9.85	0.1	2.3
Tris(2-ethylhexyl) Trimellitate	569.3812	0.0	264.3	−1.59	9.50	0.1	1.6
Erucamide	360.3235	−0.2	198.3	−1.73	8.62	0.2	6.5
N,N′-Diphenyl-p-phenylenediamine	283.1212	0.7	170.1	−1.9	6.39	0.1	1.1
Polypropylene Glycol (PPG 5)	261.1306	−0.3	146.7	−2.0	2.57	0.1	8.3
Bis(2-(2-butoxyethoxy)ethyl) Phthalate	455.2639	−0.1	208.7	−0.55	6.76	0.2	1.0
Methyl 3-(3,5-di-tert-butyl−4-hydroxyphenyl)propionate	315.1931	0.0	177.4	0.0	7.03	0.1	3.2
methyl 9,10-dihydroxyoctadecanoate	337.2713	0.0	193.14	0.1	8.13	0.0	12.3

Hexadecyl methacrylate (HDMA) was exclusively detected in migration extracts from samples P and H, and was also present in their associated labels and outer wrappers. This strongly suggests that the source of this compound is the external printed packaging. This finding is supported by the PCA, which shows P and H as distinct from the rest of the dataset, indicating a unique chemical signature. HDMA is a long-chain alkyl methacrylate widely used in surface treatments and UV-curable ink formulations due to its hydrophobicity, gloss, and film-forming properties (Boucher, n.d.). Its presence in food contact materials has been previously documented, including its migration from pizza box cardboard as reported by Sapozhnikova et al (Sapozhnikova & Nuñez, 2022). HDMA is listed under Annex 10, Part B of the Swiss FDHA Ordinance on food contact materials, which mandates that non-evaluated substances must not be detected above 0.01 mg/kg in food or simulants using valid analytical methods.

The restricted occurrence of HDMA in only two samples, despite similar tea formulations and packaging formats, points to formulation-specific differences in ink or coating composition. Its selective appearance may reflect specialized surface treatments used to achieve aesthetic or barrier properties in certain packaging lines.

Tetradecyl Methacrylate was more broadly detected across samples, appearing in H, HM, HPM, P, PPM, and PPMTV, and consistently in their labels and external wrappers. Tetradecyl methacrylate, like HDMA, is commonly used in paper coatings and UV inks. It is also listed in Annex 10, Part B of the FDHA regulation, with the same maximum permitted migration of 0.01 mg/kg. Its widespread detection suggests that this compound is a routine component in certain ink formulations used across multiple brands. The repeated detection across structurally similar samples from different infusion types confirms that its presence is unrelated to tea content and is instead linked to external material design.

Acetyl Tributyl Citrate (ATBC) was present in all samples, and was consistently identified in both the packaging materials and the migration extracts. This compound functions as a plasticizer in ink formulations and is often found in printed papers used in food packaging (Wang et al., 2015). ATBC is approved under Regulation (EU) No 10/2011, although no specific migration limit (SML) is set. However, migration must comply with the overall safety requirement of 10 mg/dm^2. Its ubiquitous presence suggests widespread use in commercial ink formulations and highlights the need for careful management of plasticizer components in non-direct food contact materials.

Benzophenone was detected exclusively in sample LB DMB, and was also found in its label and outer wrapper. This compound is a well-known photoinitiator used in UV-curable inks and has been widely reported in studies on food packaging migration (Kejlová et al., 2019; Lago & Ackerman, 2016; Liu & Mabury, 2019). Its specific migration limit is 0.6 mg/kg. The PCA results confirm that LBPPM is chemically distinct from other samples, aligning with the presence of this compound. Benzophenone's selective appearance suggests either specialized UV printing processes or a different supplier chain for this packaging batch. Given its established toxicological concerns, its presence in a single sample reinforces the importance of strict quality control in ink sourcing.

Caffeine was detected in the packaging of samples H, P, TTT, and LB, as well as in all envelopes and labels. As caffeine is an intrinsic component of tea, its detection in the packaging materials is indicative of reverse migration—from the tea infusion into the surrounding materials. This process may occur via sublimation, absorption, gas-phase diffusion, or condensation, especially under hot brewing conditions. While this does not represent a safety concern per se, it highlights potential weaknesses in the barrier properties of packaging materials and may lead to unintended loss or degradation of active ingredients in the product.

Didodecyl 3,3′-Thiodipropionate was found only in sample H, both in the migration extract and its packaging components. It is a thioester antioxidant used in plastics, adhesives, and inks to inhibit oxidative degradation (Liu et al., 2023). According to Regulation (EU) 10/2011, it has an SML of 5 mg/kg. The unique presence of this compound, in conjunction with HDMA, further explains the distinct clustering of H in the PCA. This suggests that specific formulations in the external packaging of H involve both antioxidants and hydrophobic coating agents.

Tris(2-ethylhexyl) Trimellitate, a plasticizer, was found in all samples except H, and was consistently detected in both the label and wrapper materials. While it is not currently listed under EU Regulation 10/2011, scientific literature has identified its estrogenic activity in vitro, classifying it as a potential endocrine disruptor, and it is included on the TEDX list (Https://Endocrinedisruption.Org/Interactive-Tools/Tedx-List-of-Potential-Endocrine-Disruptors/Search-the-Tedx-List). For substances suspected of having endocrine-disrupting properties and lacking adequate toxicological data, EFSA recommends applying a specific migration limit (SML) derived from the Threshold of Toxicological Concern (TTC). In such cases, a conservative TTC-based value of 0.15 mg/kg food is proposed as a default SML to ensure a high level of consumer protection in the absence of substance-specific evaluations (EFSA, 2019). The fact that it was absent in sample H—which showed a markedly different overall profile—further supports the influence of ink formulation on migration behavior. Given the growing concern over endocrine-disrupting chemicals (EDCs), the regular appearance of this compound warrants further toxicological attention.

Erucamide was found in all samples except H, both in packaging and migration extracts. It is used as a slip agent in inks and coatings and is regulated under EU 10/2011 with an SML of 5 mg/kg. Its absence in H again marks this sample as chemically distinct. The broad presence of erucamide across other samples indicates its widespread use, but also underscores the need to evaluate its behavior in high-temperature scenarios like tea infusion.

N,N′-Diphenyl-p-phenylenediamine was detected in samples H and P, and in their respective wrappers and labels. It is not currently covered under EU food contact regulations but appears on the TEDX list as a suspected endocrine-disrupting compound (Akahori et al., 2008). Its presence in only two samples suggests either specific use in their packaging formulations or contamination related to particular ink systems. Given its potential health implications and lack of regulatory oversight, this compound should be a priority for further evaluation. As with the previously mentioned compound, the specific migration limit (SML) will be set at 0.15 mg/kg food, following the TTC-based approach recommended by EFSA for substances suspected of endocrine-disrupting activity and lacking comprehensive toxicological data (EFSA, 2019).

Polypropylene Glycol (PPG) was found only in LBDMB, both in the migration extract and packaging materials. This compound is commonly used in inks as a solvent, plasticizer, dispersing agent, and humectant, enhancing ink flexibility and moisture retention. While it is permitted under Regulation (EU) 10/2011 without an individual SML, its presence must not exceed the general migration limit of 10 mg/dm^2. The PCA confirms that LBDMB is chemically distinct, supporting the conclusion that PPG contributed to its unique profile.

Bis(2-(2-butoxyethoxy)ethyl) Phthalate (CAS 16672-39-2) was also detected only in LBDMB, this phthalate compound was found in both packaging and migration extract. It has been previously reported as a migrant from paper inks (Carlos et al., 2021; Li et al., 2018). Currently not listed in Annex I of Regulation (EU) 10/2011, its toxicological evaluation is incomplete. In the absence of adequate safety data, its acceptable migration is derived via the Threshold of Toxicological Concern (TTC) approach. The Threshold of Toxicological Concern (TTC) is a risk assessment approach used to establish safe exposure limits for chemicals when specific toxicological data is lacking. It is based on the principle that low-level exposures to certain chemicals, grouped by structural and toxicity characteristics, pose minimal risk. Substances are categorized into Cramer classes (I–III), with Class I representing the lowest concern and allowing higher thresholds. This compound was classified under Cramer Class I, with a derived SML of 1.8 mg/kg (EFSA, 2019). Its selective appearance in a single sample is notable and may reflect a non-standardized or outdated ink formulation.

Methyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate was detected in the migration extract of sample H, as well as in its corresponding label and envelope. Its presence aligns with the distinct grouping of this sample in the PCA analysis (Figure X and Figure XX). This compound is a known degradation product of Irganox 1076, a widely used antioxidant, and is considered a non-intentionally added substance (NIAS) (Estremera et al., 2024). As it is not currently included in Annex I of Regulation (EU) No 10/2011, its toxicological profile remains incomplete. Based on its structure, it has been classified as a Cramer Class II substance, with a derived Specific Migration Limit (SML) of 0.54 mg/kg of food.

The compound methyl 9,10-dihydroxyoctadecanoate has been found migrating from samples H and P, therefore corresponding to the PCA results, and its envelopes and labels. This compound has been reported to migrate from recycled cellulose materials (An et al., 2024) and from migration to paper straws (Rusko et al., 2020). Since it is not currently listed in Annex I of Regulation (EU) No 10/2011, its toxicological profile is still considered incomplete. Based on its chemical structure, it has been assigned to Cramer Class II, with a derived Specific Migration Limit (SML) of 0.54 mg/kg of food.

As can be seen in Fig. 3, none of the migration values exceed the established migration limits described above.

4. Conclusions

This compound-focused analysis reinforces the central finding that external printed packaging materials—though not in direct contact with food—can significantly influence migration behavior in food products. Some compounds, such as ATBC, tetradecyl methacrylate, and erucamide, were found consistently across most samples, reflecting their widespread use in modern packaging inks. Others, including HDMA, benzophenone, PPG, and various phthalates, appeared sporadically but with strong correlations to distinct PCA clustering, implying more specialized or outdated formulations. Importantly, although the immersion of the external printed layer constitutes a worst-case scenario, these conclusions relate specifically to the migration originating from the tea bag under realistic preparation conditions, i.e., immersion in 200 mL of boiling water for 30 min.

The detection of reverse migration (e.g., caffeine moving from tea to packaging) underscores not only the bidirectionality of migration processes but also the potential for active components in food to interact with packaging materials. This phenomenon may compromise product integrity.

Moreover, the repeated detection of potential endocrine disruptors, including trimellitate, diphenyl-p-phenylenediamine, and phthalates, raises important regulatory and health concerns. Many of these substances are either not included in current legislation or are governed only by general limits, despite their known or suspected biological effects.

Furthermore, this study also demonstrates the effectiveness of the UPLC-IMS-QTOF analytical technique, particularly when combined with extensive compound databases. This approach enabled the reliable identification and quantification of both IAS and non-intentionally added substances (NIAS), even at low detection limits, proving to be a robust and sensitive tool for the safety assessment of complex packaging systems.

Together, these findings underscore the urgent need for comprehensive risk assessments that address both direct and indirect food contact materials—including printed papers and inks—and incorporate advanced analytical strategies capable of detecting a broad spectrum of potential migrants.

CRediT authorship contribution statement

Paula Vera: Writing – original draft, Supervision, Investigation, Conceptualization. **Nerin Cristina:** Resources. **Canellas Elena:** Writing – original draft, Validation, Supervision, Resources, Investigation, Funding acquisition, Formal analysis, Conceptualization.

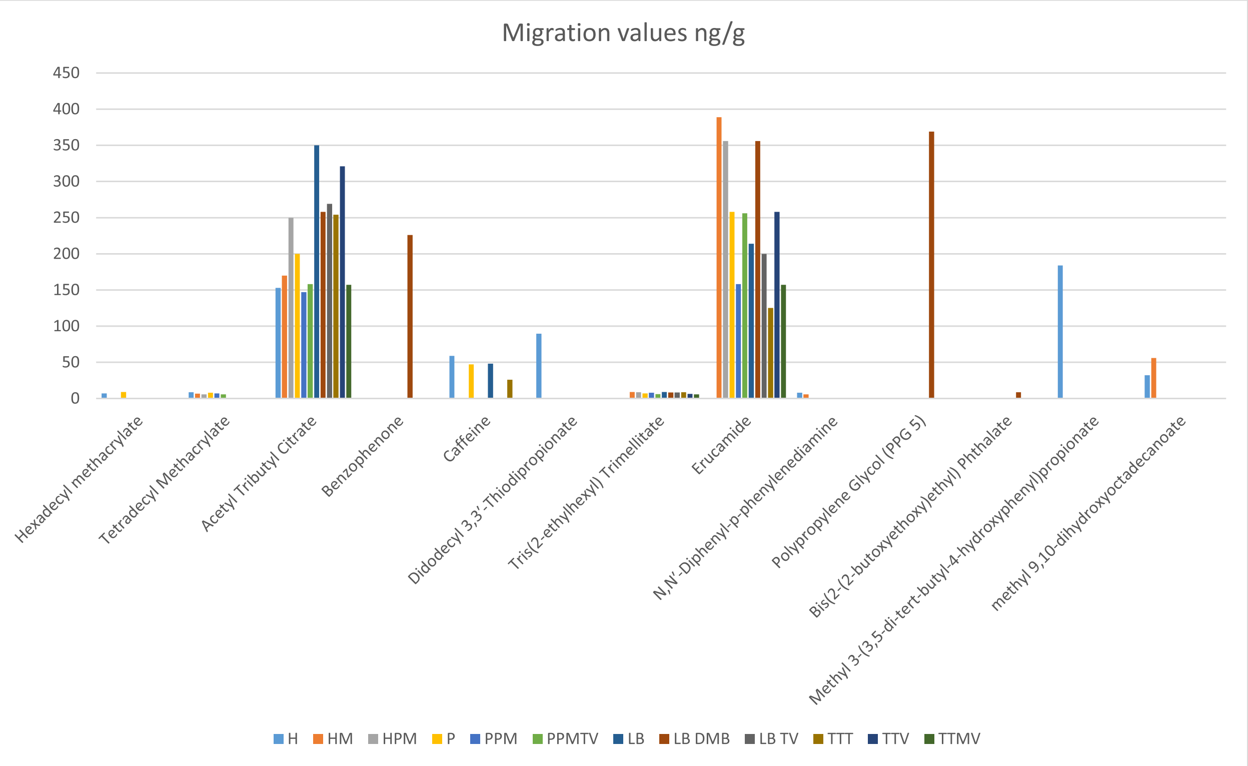

Fig. 3. Migration values obtained for the samples analyzed expressed as ng/g.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Elena Canellas reports a relationship with the grant RYC2021-034150-I funded by MCIN/AEI/ 10.13039/501100011033 and by the "European Union Next Generation EU/PRTR" that includes: funding grants and paid expert testimony.

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Data availability

No data was used for the research described in the article.

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