Migration of Antimony and Phthalate Esters from Plastic Food Packaging: A Systematic Review of Reported Levels, Food Matrix Effects and Influencing Factors

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Abstract

Plastic food packaging represents a major source of chemical exposure, as materials such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC) can release toxic elements including antimony (Sb) and phthalate esters (PAEs) into foods, raising growing concerns for public health and regulatory compliance. This review followed the PRISMA 2020 protocol and systematically screened 1,317 records from ScienceDirect, PubMed, and Scopus, retaining 45 original studies published between 2010 and 2025 that quantitatively assessed Sb or PAE migration from plastic food packaging. Among these, 32 articles (71.11%) investigated phthalate migration, 12 studies (26.67%) focused on antimony, and only one (2.22%) addressed both. Antimony migration, mainly from Polyethylene terephthalate (PET) bottles, was reported across 13 studies, with concentrations in bottled water generally below 5 µg/L under ambient storage, but reaching up to 18.5 µg/L in stress conditions such as high temperatures or acidic simulants. In soy sauce, total Sb levels were reported up to 6.6 µg/L, while fruit juices and carbonated drinks showed higher migration than plain water. For phthalates, analysis of 32 studies revealed consistently higher levels in lipid-rich or acidic matrices. In bottled waters, DBP, DEP, and DEHP ranged from non-detectable to 25 µg/L, with cumulative increases during storage up to 1283

days. Edible oils showed much higher concentrations, reaching mg/L levels of DBP, BBP, and DEHP, while convenience foods such as cakes contained DEHP up to 5.2 mg/kg. Milk products also revealed significant accumulation of DEP, DBP, and DEHP under refrigeration and ambient storage. Factors most strongly associated with increased migration included elevated temperatures (40-70 °C), prolonged storage (months to >1 year), and matrix composition (acidic or fatty foods). Despite regulatory limits of 5 µg/L for Sb and 1.5 mg/kg for DEHP, several studies reported exceedances under stress conditions. This synthesis provides a critical basis for risk assessment and calls for harmonized migration testing and regulatory updates covering non-aqueous foods and combined exposures to Sb and PAEs.

Introduction

The use of plastic packaging in the food industry has expanded considerably over the past decades, driven by its low production cost, light weight, ease of transport, and preservation properties that help extend food shelf life.[1,2] Polymers such as polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are particularly favored because they provide effective barriers against moisture, oxygen, and light, while being adaptable to a wide variety of shapes and uses.[3,4] These features make them essential materials for bottling water and beverages, packaging dairy products, oils, processed foods, and ready-to-eat meals.[5,6] However, this widespread use is accompanied by growing concerns regarding the migration of chemical substances from packaging into foods, especially under the influence of temperature, storage time, and the nature of the food matrix.[7,8] Numerous studies have demonstrated that these materials are not inert barriers and can release various chemical compounds into food during storage or transport.[9-14] Among these substances, antimony and phthalate esters attract particular attention due to their recurrent presence and potential health effects.

Antimony (Sb) is commonly used as a catalyst in the production of polyethylene terephthalate (PET), the most widely employed plastic for water and beverage bottles.[15,16] Although generally present at residual levels, it can migrate into foods and beverages, with concentrations varying according to temperature, contact duration, and the type of liquid packaged.[9,17,18] Exceedances of regulatory limits have been reported under certain extreme conditions, highlighting the need for continuous monitoring.[19]

Phthalate esters (PAEs), used as plasticizers to improve polymer flexibility, represent another major group of contaminants identified in packaged foods.[8,6] These lipophilic compounds tend to accumulate preferentially in fatty or acidic matrices, such as oils, milk, or juices, and their migration is strongly influenced by temperature and storage duration.[3,20,21] Among them, DEHP, DBP, and BBP are frequently detected and often studied for their toxicity and endocrine-disrupting potential.[7,22]

The toxicological implications of these migrations are well documented. Chronic exposure to antimony has been associated with adverse effects on the liver and lungs;[23] while several phthalates are classified as reproductive toxicants or endocrine disruptors.[22,24] In this context, many countries have established specific migration limits (SMLs) for these substances, such as 5 µg/L for antimony in water (EU Regulation 10/2011) and 1.5 mg/kg for DEHP.[22] Despite this regulatory framework, the scientific literature reveals great variability in measured levels, reflecting the diversity of polymers, storage conditions, and food matrices studied.[5,25,26] Therefore, a systematic synthesis of available data is needed to better characterize the extent of migration.

Despite numerous publications addressing antimony or phthalate migration, most previous works have investigated these contaminants separately and have primarily focused on bottled water or simple aqueous matrices. Very few studies have compared migration patterns across diverse food

types or considered the combined influence of time, temperature, and matrix composition under real storage conditions. Moreover, there is still a lack of integrated synthesis linking the reported migration levels with international regulatory thresholds. The present review therefore aims to bridge these gaps by providing a comprehensive and comparative analysis of both Sb and PAE migration from plastic food packaging across multiple food matrices, based on 45 studies published between 2010 and 2025.

The objective of this systematic review is thus to evaluate, based on the scientific literature, the levels of migration of antimony and phthalate esters from plastic packaging into foods, in order to identify the reported concentrations and the conditions that favor this migration.

Materials and Methods
Literature Search
A systematic review was conducted using three online databases (Scopus, PubMed, and ScienceDirect) to identify studies addressing the migration of antimony and phthalate esters from plastic packaging into foodstuffs, with a focus on the reported concentrations and the conditions favoring such migration. The search was carried out in accordance with the PRISMA guidelines.[27] Queries were constructed using Boolean operators and keywords, relying on two main search equations. The search strings used were ("antimony" OR "Sb") AND ("migration" OR "leaching") AND ("food" OR "food simulant") AND ("plastic packaging") as well as ("phthalates" OR "phthalate esters") AND ("migration" OR "leaching") AND ("food" OR "food simulant") AND ("plastic packaging"). Keywords were adapted according to the specifications of each database. The search covered the period from 2010 to September 3, 2025, without applying additional filters. The literature search was performed in English, and only articles published in this language were considered. The search resulted in the identification of 1,239 records from ScienceDirect, 62 from PubMed, and 16 from Scopus after applying the two search equations.

Inclusion and Exclusion Criteria
A total of 1,317 references were collected from all the databases consulted. The files were exported in RIS format for most of the databases, with the exception of PubMed, where the specific PubMed format was used. All references were then imported into EndNote X9, which enabled the detection and removal of 113 duplicates through both automated processing and manual verification. As a result, 1,204 unique references were obtained, converted into XML format, and imported into the SysRev platform for the selection process. The inclusion and exclusion criteria applied are presented in Table 1. Based on these criteria, titles and abstracts were screened, leading to the preselection of 86 articles that were subjected to full-text review for detailed analysis. During the final eligibility assessment, only original experimental or analytical studies were retained for the extraction of relevant quantitative data. At the end of this process, 45 publications were included in the final analysis. The overall selection process is illustrated in Fig 1.

Table 1: Inclusion and exclusion criteria applied to studies in SysRev

Inclusion	Exclusion
Studies investigating the migration of antimony (Sb) or phthalate esters from plastic packaging into foods or food simulants	Studies not addressing food or food simulants
Studies providing details on migration conditions (temperature, contact time, type of food or simulant, and type of plastic)	Studies not reporting numerical migration values (e.g., expressed in µg/L or mg/kg)
Only studies published from 2010 onwards were included.	Studies published before 2010

Identification of new studies via databases and registers

Identification

Records identified from:
Databases (n = 1,317):
ScienceDirect (n = 1,239)
PubMed (n = 62)
Scopus (n = 16)

→ Records removed before screening:
Duplicate records (n = 113)

Screening

Records screened
(n = 1,204)

→ Records excluded
(n = 1,118)

Reports sought for retrieval
(n = 86)

→ Reports not retrieved
(n = 0)

Reports assessed for eligibility
(n = 86)

→ Reports excluded:
Studies that do not focus on
plastic packaging (n = 41)

Included
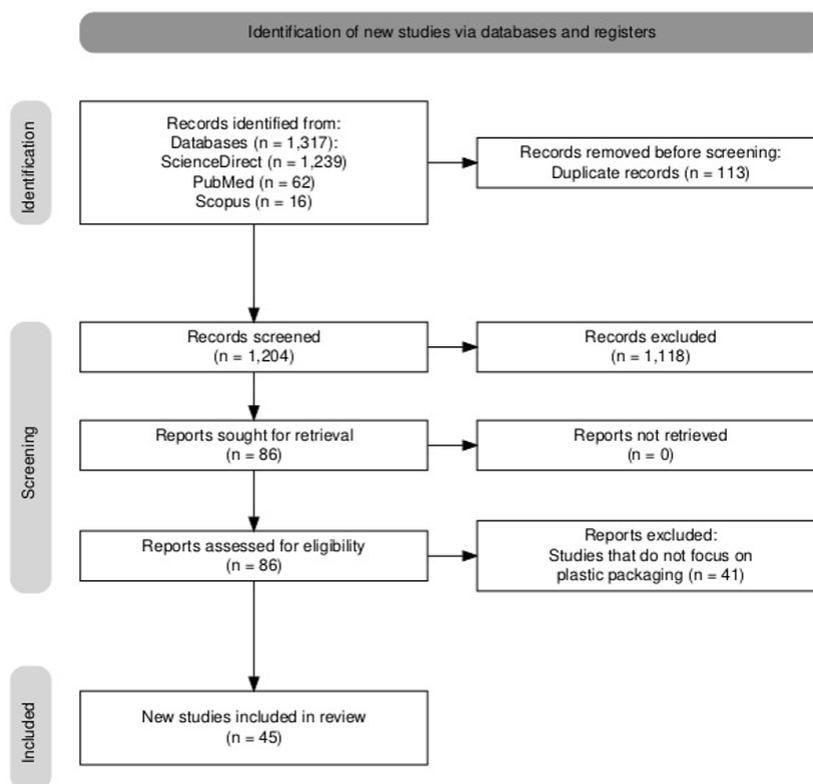
New studies included in review
(n = 45)

Fig. 1: PRISMA flow chart showing the study selection process

Data Extraction Process

Data were extracted from the selected studies based on the following parameters: author(s) and year of publication, type of food or simulant studied, type of plastic investigated (PET, PVC, PE, PP, etc.), and nature of the packaging (bottles, films, trays, etc.). Migration conditions, including exposure temperature (ambient, refrigeration, heating, pasteurization, etc.) and contact duration (hours, days, months), were also recorded. Reported concentrations of antimony (Sb) and phthalate esters (DEHP, DBP, BBP, etc.) were collected, along with the observed value ranges (minimum-maximum) and the regulatory standards applied for their interpretation. All extracted information was compiled and organized using Microsoft Excel®.

Scope of the Article

This systematic review examines the migration of antimony (Sb) and phthalate esters (PAEs) from plastic food packaging into different food matrices. Particular emphasis is placed on polyethylene terephthalate (PET) bottles, which dominate the literature, and on conditions that influence migration such as temperature, storage duration, and food composition. The review synthesizes reported concentration levels, comparing them with international regulatory limits, and evaluates how matrix characteristics (aqueous, acidic, or lipid-rich) modulate the extent of chemical release. Special attention is given to the differential patterns of Sb migration in bottled waters versus more complex beverages, and to the markedly higher accumulation of phthalates in fatty foods and oils. By critically analyzing 45 studies published between 2010 and 2025, this review identifies consistent determinants of migration (time, temperature, matrix effects), highlights knowledge gaps such as the limited exploration of Sb beyond water, and underscores the need for harmonized testing protocols. Studies addressing combined exposures, polymer diversity beyond PET, and mechanistic insights into diffusion and solubility processes are given particular consideration to inform future risk assessment and research priorities.

Results

This review presents the distribution of studies according to the type of contaminants investigated and the temporal evolution of publications, which remain included in this section. The other main findings regarding migration levels, influencing factors, and food matrix effects have been fully examined and are discussed in detail in the Discussion section.
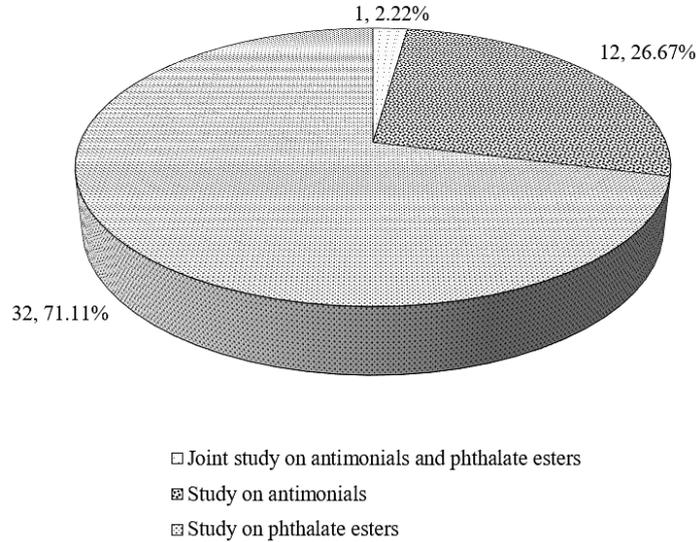

□ Joint study on antimonials and phthalate esters

⊠ Study on antimonials

⊞ Study on phthalate esters

Fig. 2: Distribution of included studies according to the type of contaminants investigated (n=45)

Distribution of Studies According to the Contaminants Studied

Fig 2 below illustrates the distribution of the 45 studies included in this review according to the type of contaminants investigated. The majority of the works (32 articles, representing 71.11%) focus on the migration of phthalate esters from plastic packaging into foodstuffs. A smaller group of 12 publications (26.67%) specifically addresses the migration of antimony. Finally, only one study (2.22%) combines the joint evaluation of antimony and phthalate esters. This distribution highlights a much stronger scientific interest in phthalate esters during the study period, while antimony appears to remain a relatively underexplored topic.
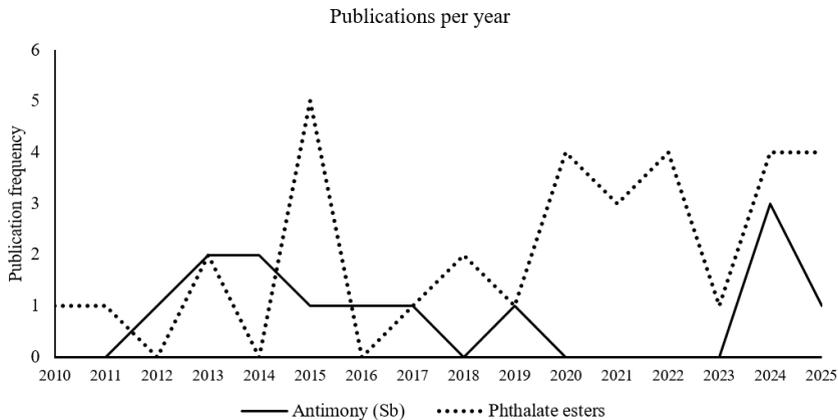

Publications per year

—— Antimony (Sb)   ••••• Phthalate esters

Fig. 3: Temporal distribution of publications on antimony and phthalate ester migration from plastic packaging (n=45)

Temporal Evolution of Publications

Fig 3 below shows the annual distribution of publications included in this review between 2010 and 2025. Studies on antimony migration appear sporadically, with a maximum of 2 articles in 2013, 2014, and 2015, followed by a generally low and irregular trend until 2025, where a slight increase is observed with 3 publications in 2024. In contrast, research on phthalate esters demonstrates a more pronounced dynamic. After a limited start between 2010 and 2013 (0 to 2 article per year), a major peak is observed in 2015 with 5 publications. Subsequently, the number fluctuates but stabilizes from 2019 onward, ranging between 1 and 4 articles per year, with peaks of 4 publications in 2020, 2022, 2024, and 2025. These findings indicate that research on phthalates has attracted increasing and consistent attention during the second half of the study period, whereas antimony remains much less investigated, with only scattered contributions.

Discussion

Antimony

Antimony (Sb) is a metalloid element with atomic number 51, belonging to the pnictogen group. It occurs in several oxidation states, mainly Sb(III) and Sb(V), which are the most relevant forms in the environment and in food matrices. Its stable crystalline structure is rhombohedral, and it is widely used industrially as a catalyst in the polymerization of polyethylene terephthalate (PET). This explains its residual presence in many plastic food packaging materials. Several studies have reported that, under certain conditions, this element can migrate from PET into beverages and food simulants.[9,12,13,20,28-31] Table 2 below provides a synthetic overview of the data extracted from the 13 included articles, highlighting the food matrices or simulants tested, the experimental conditions applied, and the levels of antimony detected.

Table 2: Migration of antimony from food plastic packaging (n = 13).

Type of food or simulant	Type of plastic studied	Type of packaging (bottles, films, trays, etc.)	Exposure temperature (ambient, refrigeration, heating, pasteurization, etc.)	Contact duration (hours, days, months)	Migrated antimony (Sb) concentration (µg/L or mg/kg)
Mineral water[9]	PET	Bottles (510 mL, light blue)	40 °C, 50 °C, 60 °C	3, 7, 10, 14, 21 days	From < LOQ (1.0 µg/L) at 40 °C to 4.38 µg/L at 60 °C (21 days)
Mineral water[12]	PET	Bottles (300-510 mL, various colors)	40 °C (Brazil), 60 °C (EU)	10 days	< LOQ (1.0 µg/L) at 40 °C; 1.59–4.42 µg/L at 60 °C
Bottled drinking water[13]	PET	Bottles (0.33 L, mostly colorless, some faint blue)	25 °C, 35 °C, 50 °C	120 and 240 days	Initial 0.025–0.062 µg/L; increased up to 2.17 µg/L at 50 °C after 240 days
Bottled water, mineral water, cola, orange-flavored carbonated drink,	PET	Bottles (25 commercial brands, Turkey)	4 °C, 25 °C, 40 °C	0, 90, 180, 365 days	Sb detected in all beverages except DW at baseline; higher migration in acidic/carbonated drinks; max

fermented turnip drink, lemonade[20]					~3.72 µg/L (lemonade, 90 d at 4 °C); most <3 µg/L
Soy sauce[28]	PET	Bottles	not defined	not defined	Inorganic Sb(III): 0.8–2.3 µg/L; Total Sb: 1.7–6.6 µg/L
Bottled water and fruit juices (orange, grape)[29]	PET	Bottles	Room temperature (centrifugation leaching for juices)	not defined	Water: Sb(V) 0.203 µg/L; Juices: Sb(V) 0.261–0.435 µg/L, Sb(III) 0.091 µg/L, TMeSb 0.263–0.670 µg/L
Bottled water (12 brands, Mexico) and ultrapure water (simulant)[17]	PET	Bottles (500 mL, colorless)	25 °C and 75 °C; pH 3 and 7	5 and 15 days	Initial: 0.28–2.30 µg/L; Migration tests up to 5.1 µg/L at 75 °C; Range: 1.1–18.5 µg/L (worst case)
Mineral water[15]	PET	Bottles (clear, light blue, dark blue, 3 brands)	4 °C, 20 °C, 40 °C, 60 °C	Up to 220 days	Initial: 0.3–0.7 µg/L; At 60 °C: 2.6–4.2 µg/L; Exceeded 5 µg/L after 15–30 days (dark blue bottles)
Bottled drinking water (16 brands, China) with Milli-Q water[18]	PET	Bottles	4 °C, 25 °C, 70 °C	1, 2, and 4 weeks	4 °C: 1.88–8.32 ng/L; 25 °C: 2.10–18.4 ng/L; 70 °C: 20.3–5436 ng/L
Mineral water (2 brands) and fruit juices (orange, lemon, apple, mango, peach)[30]	PET	Bottles	Room temperature; prolonged storage	Up to 2 months (water); not defined (juices)	Water: 27–75 ng/L; Juices: 531–966 ng/L
Bottled beverages (water, juice, tea, coffee, carbonated drinks) and simulants (water, acetic acid, ethanol)[31]	PET	Bottles (80 brands, Japan)	25 °C, 40 °C, 55 °C, 70 °C	Up to 440 days	Bottled drinks: 0.3–1.6 µg/L; Migration in simulants: <1 µg/L (25–40 °C), up to 14.4 µg/L (80 °C, 72 h)
Distilled water, 3% acetic acid, 10% ethanol, 20% ethanol,	PET	Bottles	40 °C (10 days); reuse test with 3% acetic acid	10 days (reuse cycles for acetic	0.5–1.2 µg/L (aqueous simulants); <LOQ in oils; vinegar: 0.45–0.50 µg/L; reuse test with acetic

olive oil, sunflower oil, wine vinegar, apple vinegar (EU food simulants)[19]			also at 40 °C; additional test at 60 °C (10 days)	acid up to 3 lea-chings)	acid reached 6.4 µg/L
Bottled water (non-carbonated, carbonated, non-carbonated enriched) [16]	PET, HDPE, PS, PC	Bottles (0.25–18.9 L, USA brands)	23 °C (room temperature, 12h/12h light-dark cycle)	1, 7, 30, 60 days	NCR: <LOQ – 500 ng/L (avg. 90 ng/L); CR: 53–383 ng/L (avg. 180 ng/L); NCRE: 77–1070 ng/L (avg. 420 ng/L); Max ~1200 ng/L (PET bottles, 60 days)

Food Matrices and Plastic Types Investigated in Antimony Migration Studies

Fig 4 (Distribution of food matrices investigated in antimony migration studies) illustrates the distribution of food types and simulants examined across the 13 included articles. The majority of studies focused on bottled water, representing 84.68% of the cases. Other beverages, including juices, cola, coffee and soft drinks, accounted for 30.76% and stimulants accounted for 15.38%. Distilled water was reported in 7.69% of studies, while soy sauce was also addressed in a single investigation (7.69%). This highlights that water, particularly mineral and drinking water, has been the primary focus of Sb migration research, whereas other beverages and specific food matrices remain less explored.

The predominance of bottled water in Sb migration studies reflects both its global consumption and its susceptibility to contamination from PET bottles. Several authors have emphasized this focus, with investigations conducted under different storage conditions and geographical contexts.[9,12,13,15-18] Beyond water, some studies extended their analyses to juices and soft drinks, reporting higher Sb levels in acidic or carbonated beverages.[20,29-31] In addition, specific food matrices such as soy sauce[28] and vinegar-based simulants Sánchez-Martínez *et al.*,[19] demonstrated measurable Sb migration, underscoring that the composition and acidity of the matrix play a critical role in Sb release. Collectively, these results confirm that water remains the most studied medium, but more complex matrices can present enhanced migration risks.
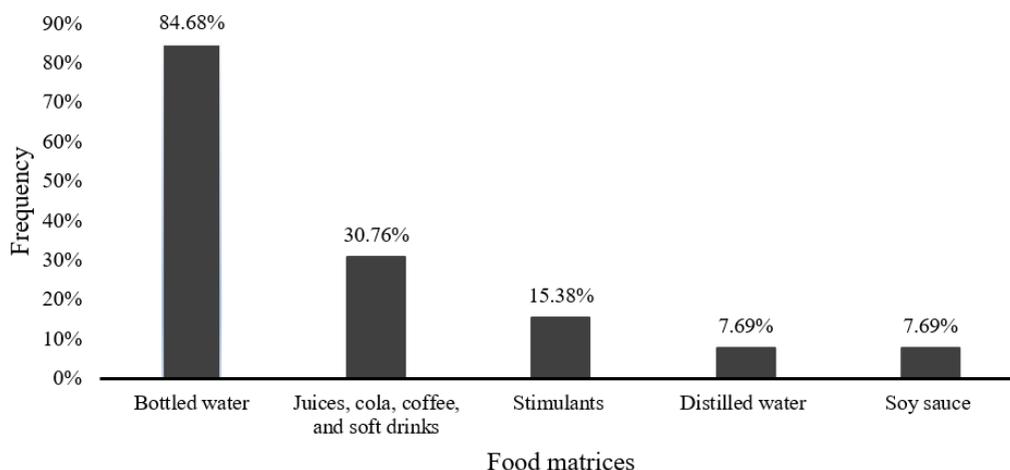

Fig. 4: Distribution of food matrices investigated in antimony migration studies(n=13)

With respect to plastic types, nearly all studies focused on polyethylene terephthalate (PET) as the dominant material of concern. Only one study expanded its scope to include additional polymers such as PVC, PE, PS, and PC alongside PET.[16] This indicates that Sb migration has been predominantly evaluated in relation to PET packaging, reflecting its widespread use for bottled water and beverages, while other plastics remain comparatively underexplored.

Across the 13 included studies, exposure temperatures varied from refrigerated conditions to high-temperature stress tests. Ambient storage at room temperature (20-25 °C) was the most common experimental condition, reported in multiple investigations as a baseline scenario reflecting typical market storage.[13,16] Refrigerated conditions (4-5 °C) were also examined in certain studies to reproduce cold-chain storage.[15,18] On the other hand, elevated temperatures of 40 °C, 50 °C, 60 °C, and even 70-75 °C were frequently applied to simulate accelerated storage, transport in hot climates, or worst-case consumer practices such as leaving bottles in cars or under direct sunlight.[9,12,17,31] A few studies additionally tested extreme scenarios, such as pasteurization or boiling conditions, reaching short exposures at 75 °C.[8,19]

The systematic use of ambient and refrigerated conditions demonstrates the effort to reproduce realistic consumer practices. Authors such as Kiyataka *et al.*,[9] and Mehdar,[13] stressed the importance of room temperature as the reference scenario, where migration is expected to remain minimal. Refrigeration, as examined by Carneado *et al.*,[15] and Fan *et al.*,[18] provides insight into the lowest exposure risk contexts, relevant for bottled water and beverages stored in controlled supply chains.

In contrast, the recurrent inclusion of high-temperature conditions across several studies highlights the scientific concern with accelerated diffusion phenomena. Elevated temperatures substantially increase the mobility of Sb within the polymer matrix and enhance its release into food or simulants, as observed by Chapa-Martínez *et al.*,[17] and Rungchang *et al.*[31] These stress conditions are not representative of normal storage, but rather serve as worst-case scenarios to test regulatory safety margins. Fan *et al.*,[18] and Sánchez-Martínez

et al.,[19] further illustrated that extreme temperatures approaching or exceeding 70 °C can lead to measurable increases in Sb release within short timeframes.

Overall, the inclusion of a wide range of temperatures across the 13 studies shows the balance between realistic consumer conditions (ambient and refrigerated) and accelerated or extreme conditions (40-80 °C). This dual approach allows researchers both to characterize typical exposure and to explore the boundaries of material safety under stress.

Effect of Storage time on Sb Release

The included studies applied highly variable contact durations, ranging from a few days to several months, in order to cover both realistic consumption scenarios and prolonged storage conditions. Short-term experiments, from 3 to 21 days, were conducted to evaluate the initial migration of Sb under accelerated or simulated conditions.[9,12,17] Other authors extended the storage period to several weeks, particularly 15 to 30 days, in order to observe intermediate-stage changes.[18] Finally, several studies prolonged the experiments to several months, with follow-ups reaching 120 to 240 days;[13] or even more than one year;[20,31] reflecting extreme storage conditions or a kinetic modeling approach. Specific investigations also explored repeated contact durations in the context of reuse or successive leaching;[19] as well as prolonged experimental conditions applied to different matrices such as juices, soy sauce, or fermented beverages.[16,28-30]

The heterogeneity of contact durations reported across the 13 studies reflects a dual methodological approach. On the one hand, short-term exposures (a few days to a few weeks) aimed to reproduce the usual consumption conditions of bottled water and beverages, where consumer exposure is generally limited. Thus, Kiyataka *et al.*,[9] and Kiyataka *et al.*,[12] selected durations of 3 to 21 days to evaluate the initial release kinetics, directly linked to the average storage period before consumption. Similarly, Chapa-Martínez *et al.*,[17] showed that significant variations could already occur within the first 5 days, especially under elevated temperatures.

On the other hand, long-term exposures, ranging from several months to more than one year, follow a logic of worst-case evaluation and

mechanistic understanding. Mehdar,[13] by extending measurements up to 240 days, highlighted that antimony migration follows a cumulative dynamic, with a progressive increase as storage time lengthens. Isci and Dagdemir,[20] and Rungchang *et al.*,[31] confirmed this trend by demonstrating that, even at levels generally below regulatory limits, very prolonged storage durations could significantly amplify Sb concentrations.

Studies on complex matrices reinforce this observation. Liu *et al.*,[28] working on soy sauce, and Lin *et al.*,[29] on juices, demonstrated that prolonged contact times promote migration in acidic or organic-rich media. Similarly, Shakerian *et al.*,[30] reported that fruit juices showed higher concentrations after several weeks of storage compared to mineral water. Finally, Sánchez-Martínez *et al.*,[19] emphasized, through successive leaching cycles with acetic acid, that both the duration and the repetition of exposure increased Sb release, particularly in reuse scenarios. Taken together, these results demonstrate that contact duration is a critical factor in antimony release. It directly influences internal diffusion within the polymer matrix and reveals the stability limits of plastic packaging. By adopting variable durations, the authors highlighted both realistic consumption scenarios and extreme situations, providing a comprehensive view of the potential risk associated with chronic Sb exposure.

Variability of Sb Migration Concentrations Across the 13 Studies

The concentrations of antimony (Sb) migrated into food matrices and simulants varied widely among the 13 included studies. In bottled mineral or drinking water, most reported values remained below the international limit of 5 µg/L, with concentrations typically ranging between 0.02 and 4.4 µg/L under ambient conditions.[9,12,13,16] However, under elevated temperatures or prolonged storage, some studies documented higher releases. For instance, Carneado *et al.*,[15] and Fan *et al.*,[18] observed exceedances of the 5 µg/L threshold in water stored at 60-70 °C for several weeks. Chapa-Martínez *et al.*,[17] reported concentrations up to 18.5 µg/L under severe storage conditions in Mexico, while Sánchez-Martínez *et al.*,[19] noted values reaching 6.4 µg/L during repeated leaching cycles with acetic acid.

Beyond water, other beverages and complex food matrices showed distinct patterns. Liu *et al.*,[28] found total Sb levels up to 6.6 µg/L in soy sauce, with inorganic Sb(III) representing a substantial fraction. Lin *et al.*,[29] measured Sb(V) in bottled fruit juices, with values up to 1.2 µg/L, while Shakerian *et al.*,[30] reported concentrations between 0.53 and 0.97 µg/L in fruit juices compared to 0.027-0.075 µg/L in mineral water. Isci and Dagdemir,[20] observed higher Sb migration in acidic or carbonated drinks, with lemonade showing levels up to 3.72 µg/L. Rungchang *et al.*,[31] examining a wide range of beverages and simulants in Japan, reported migration values up to 14.4 µg/L under high-temperature conditions.

The variability in reported Sb concentrations reflects the interplay of multiple factors, notably matrix composition, storage time, and thermal conditions. In general, bottled water consistently showed the lowest Sb migration under ambient or refrigerated storage, confirming its relative stability.[9,13,16] However, the exceedances documented under high temperatures;[15,17,18] highlight the susceptibility of PET packaging when exposed to stress conditions that accelerate diffusion processes. Sánchez-Martínez *et al.*,[19] further emphasized that repeated contact and re-use scenarios can amplify Sb release, raising concerns for consumer practices that diverge from single-use recommendations.

Beyond individual studies, a broader comparative interpretation reveals that variations in Sb migration across the literature are not only linked to experimental factors but also to differences in analytical detection limits and bottle color or resin formulation. Moreover, the predominance of PET in the reviewed studies limits our understanding of Sb release from alternative polymers indicating a gap in the literature that warrants further investigation. The role of the food matrix emerges as equally important. Studies on complex liquids demonstrated that acidic or sugar-rich environments can enhance Sb release compared to plain water. Liu *et al.*,[28] and Lin *et al.*,[29] showed that soy sauce and fruit juices led to measurable Sb levels, while Shakerian *et al.*,[30] highlighted the higher migration potential in fruit juices compared to mineral water. Isci and Dagdemir,[20] added evidence from carbonated and

acidic beverages, showing measurable increases in Sb concentrations, with lemonade yielding the highest levels in their dataset. Rungchang *et al.*,[31] confirmed that multiple beverage categories, under stress conditions, could approach or exceed regulatory thresholds.

Taken together, these findings demonstrate that while antimony concentrations generally remain within regulatory limits under normal storage, prolonged contact, elevated temperatures, and complex matrices can substantially increase Sb release. The results across the 13 studies collectively indicate that risk assessments must integrate not only packaging material but also storage scenarios and matrix-specific interactions.

Critically, this synthesis underlines that regulatory compliance under standard laboratory tests does not always translate to real-world safety margins. Field-relevant scenarios such as repeated bottle use, exposure to sunlight in transport vehicles, or acidic beverage formulations may create localized exceedances beyond the 5 µg/L SML for Sb. Few studies have explicitly modeled these realistic exposures, underscoring the need for harmonized migration testing that incorporates dynamic temperature cycles and long-term storage simulations.

Phthalate Esters

Phthalate esters represent a structurally homogeneous family, defined by a benzene aromatic ring substituted in the ortho position by two ester groups derived from phthalic acid (1,2-benzenedicarboxylic acid). This common motif, $C_6H_4(COOR)_2$, explains their designation as 'diesters', while the nature of the alkoxy side chains imparts specific properties to each molecule. Variations in chain length, degree of branching, and aromatic or aliphatic character modulate lipophilicity, volatility, and compatibility with polymers, which directly influence migration kinetics from packaging materials.[8,20,25,32-37] The studies included in this review mainly focused on two broad categories of phthalates: short- and medium-chain compounds such as dimethyl phthalate (DMP), diethyl phthalate (DEP), di-n-butyl phthalate (DBP), di-isobutyl phthalate (DiBP), and benzyl butyl phthalate (BBP); and long-chain phthalates or technical mixtures such as di-(2-ethylhexyl) phthalate (DEHP), diisononyl phthalate (DINP), diisodecyl phthalate (DIDP), and di-n-octyl phthalate (DNOP), investigated under real contact conditions with water, juices, beverages, or oils, as well as in food simulants.[38-45]

Short- and medium-chain compounds exhibit specific characteristics. DMP and DEP, due to their small size and relative polarity, are often detected at trace levels in bottled waters, with DEP frequently reported in several European countries at measurable concentrations.[8,46-49] DBP and DiBP, respectively linear and branched, are commonly co-detected with DEHP in PET-bottled water, with their presence strongly correlated with storage time and temperature.

Among the heavier phthalates, DEHP remains the most prominent. This compound, whose branched C□ side chains confer strong lipophilicity, is often the most abundant in still mineral waters bottled in PET, as highlighted by Keresztes *et al.*,[6] Tables 3a-3c below summarize the characteristics and results of studies on phthalate ester migration from plastic food packaging, categorized by food matrix, in highlighting the experimental conditions applied, and the levels of phthalate esters detected.

Food Matrices and Plastic Types Investigated In Phthalate Esters Migration Studies

The analysis of the 33 included studies shows that the majority of migration assessments have been performed in bottled water (46.87%), followed by juices and carbonated beverages (15.62%), milk (12.50%), convenience foods (9.37%), food simulants (9.37%), edible oils (6.25%), and distilled water (3.12%), as illustrated in Fig 5 (Distribution of food matrices investigated in phthalate ester migration studies). This predominance of water reflects the central role of PET bottles in human exposure pathways and the commercial ubiquity of this matrix. Indeed, numerous investigations have demonstrated that PET-bottled waters are prone to phthalate release, with increases particularly evident under elevated temperature or extended storage. For instance, Zaki and Shoeib,[8] reported a temperature-dependent increase in DEHP and DBP concentrations in Egyptian bottled waters, while Keresztes *et al.*,[6] highlighted a clear accumulation of DEHP and DBP in non-carbonated mineral waters stored over long durations in Hungary. Similar trends were documented in Spain and Portugal, where DEP, DBP, and DEHP were consistently detected in PET-bottled waters;[4,48] confirming that water is a critical medium for evaluating phthalate esters migration.

Table 3a: Migration of phthalate esters from plastic packaging into other beverages and dairy products (n=10)

Type of food or food simulant	Type of plastic studied	Nature of packaging (bottles, films, trays, etc.)	Types of phthalate esters migrated	Exposure temperature (ambient, refrigeration, heating, pasteu-rization, etc.)	Contact duration (hours, days, months)	Concentration of migrated phthalate esters (DEHP, DBP, BBP, etc.)
Milk bottles[11]	PS, PET, HDPE, PP	Milk bottles, cream/ cheese containers, disposable cups	DMP, DEP, BBP	Room temperature; UV-aging	Not precisely defined	PS cream container: up to 195 ng/mL (milk); PET: up to 77.4 ng/mL
Bottled beve-rages (DW, MW, cola, OFCD, FTD, lemonade)[20]	PET	Plastic bottles	DMP, DEP, DBP, BBP, DNOP, DEHP, DINP, DIDP	4 °C, 25 °C, 40 °C	0–365 days	DEP: up to 6.34 ng/mL; DBP: ND–5.49; DEHP: ND–8.06; DINP: up to 37.3 ng/mL
Soda and mbeverage msamples[33]	Not defined	Plastic bottles	DIBP, DNBP, DEHP	Not defined	Not defined	DIBP: 232 EF; DNBP: 301 EF; DEHP: 475 EF (20–400 µg/L spiking)
Fruit juices (orange, pome-granate, apricot)[10]	PET	Plastic bottles	DEP, DBP, DIBP, DEHP	25 °C, 4 °C, 40 °C	1–45 days	DEP: 325 EF; DBP: 345 EF; DIBP: 355 EF; DEHP: 375 EF; Recoveries: 65–75%
Distilled water; vinegar, mint extract, salty leaves, pickled cucumber, lemon juice[25]	PET	Plastic bottles	DEHP, DBP, BBP	25 °C, sunlight, °C, 40 °C	10–90 days	DEHP: 137ng/L; DBP: 4010–8432 ng/L; BBP: 4191– 6480 ng/L

Sample	Material	Container	Phthalates	Conditions	Duration	Results
Fruit juices (cherry, peach, apricot, apple)[35]	PET	Plastic bottles	DEP, DBP, DEHP, DNOP, DINP, DIDP	Refrigerated; LC-MS/MS 40 °C column	Not precisely defined	DEP: <LOD–32.62 ng/mL; DBP: 1.05–3.18 ng/mL; DEHP: 1.78–5.24 ng/mL; DINP: 20.55–31.19 ng/mL
Milk (China)[32]	PET	Plastic bottles	DBP, DEHP, BBP	4 °C, 20 °C, 40 °C	20 days	DBP up to 1.56 µg/L; DEHP up to 1.72 µg/L; BBP up to 0.61 µg/L
Acidic juices (lemon, vinegar, verjuice, Iran)[1]	PET	Bottles/containers	DMP, DEP, DnBP, BBP, DEHP, DnOP	Room temp 25 °C; sunlight exposure	Up to 57 days (pred. 365 days)	Median: DEHP 9.8; DnBP 7.9; BBP 4.0; DEP 2.1; DMP 5.2; DnOP 4.9 µg/L
Pasteurized bottled milk (Iran, 11 brands)[41]	PET	Plastic bottles 946–1000 Ml	DMP, DEP, DBP, DEHP, DnOP	Refrigeration 4–5 °C	1–4 days	Mean: DnOP 779.3 > DEHP 383.6 > DBP 328.4 > DEP 8.0 > DMP 3.4 ng/L
Whole milk (China)[21]	Plastic	Bottles (plastic, glass, metal)	DMP, DEP, DIBP, DEHP	4 °C storage; ambient prep	Not defined	DEP: 2.6–68.3 ng/g; DIBP: 4.8–26.3 ng/g; DEHP: 6.0–79.3 ng/g

Table 3b: Migration of phthalate esters from plastic packaging into solid, semi-solid food, food simulants and plastic extracts (n=9)

Type of food or food simulant	Type of plastic studied	Nature of packaging (bottles, films, trays, etc.)	Types of phthalate esters migrated	Exposure temperature (ambient, refrigeration, heating, pasteu-rization, etc.)	Contact duration (hours, days, months)	Concentration of migrated phthalate esters (DEHP, DBP, BBP, etc.)
Pap (maize porridge, Cameroon)[36]	PP	Paint buckets	DEHP, DBP, BBP, DNOP, DINP, DIDP	DEHP, DBP, BBP, 4 °C, 50–90 °C	1–72 h; up to 180 min kinetics	>50 µg/L total PAEs at 70–90 °C, pH ≤4 or ≥10
Pickled vege-tables (Iran)[39]	PET	Containers (bottles/jars)	DMP, DEP, DnBP, BBP, DEHP, DnOP	Ambient 25 °C; sunlight exposure; acidic pH	Up to ~57 days (pred. 1 year)	Means: DMP 0.069; DEP 0.118; DnBP 1.56; BBP 0.061; DEHP 6.35; DnOP 1.12 mg/kg
Convenience foods (beans, meat, cakes, potato, fish, milk)[2]	PE (films)	Plastic packaging	DEHP, DBP	−4.3–25.1 °C	Up to 150 days	DEHP: <LOD–5.23 mg/kg; DBP: 0.51–2.54 mg/kg
Edible oils (Turkey: olive, sunflower, corn, hazelnut, canola)[3]	PET	Bottles/containers	DMP, DEP, DBP, BBP, DOP	25 °C (some 4 °C)	Not defined	Virgin olive: DBP 0.049–1.875 mg/L, BBP 0.212–2.055 mg/L; Sunflower up to 1.778 mg/L DBP
Virgin olive oil (Spain)[49]	PET	Bottles (PET, glass)	DIBP, DBP, BBP, DEHP	250 °C incubation; 80–115 °C HS	8–12 months storage	PET: DIBP 120–216 µg/kg; DBP 97–175; BBP 173–211; DEHP 543–840 µg/kg; Glass: BBP 87–112; DEHP 198–237 µg/kg

Matrix	Material	Product	Phthalates	Temperature	Time	Results
Plastic leachates from 13 consumer products[14]	PVC mainly	Household plastic items	DMP, DEP, DBP, DHP, DIBP, DINP, DIDP, MEHP, DEHP, DPP, BBP, DCHP, PA	Ambient (24 h methanol extraction)	24 h	LOD ~1.4 pg/mL; recoveries 96–103%; quantitative up to 50 ng/Ml
Food simulants: heptane, ethanol, wate[r43]	PVDC	PVDC films	DEHP	25 °C, 60 °C, 80 °C	Up to 10 h	Migration up to several µg/g (higher in heptane)
Food simulants: isooctane, ethanol, acetic acid, sucrose solution[45]	PE	Films	BEHP (DEHP), BBP	−18 °C, 4 °C, 20 °C, 40 °C, 60 °C	Up to 240 h	BEHP up to 1.64 mg/kg; BBP up to 0.45 mg/kg
Beverage simulants (distilled water, 3% acetic acid)	PET	Bottles, cups	22 PAEs (incl. DIBP, DBP, DEHP, DNOP, DINP, DIDP)	40 °C	10 days	Traces: DIBP up to 48.5 ng/kg; DBP up to 498.8 ng/kg; DEHP up to 4 ng/kg; DNOP up to 18.1 ng/kg

Table 3c: Migration of phthalate esters from plastic packaging into bottled and drinking water (n=14)

Type of food or food simulant	Type of plastic studied	Nature of packaging (bottles, films, trays, etc.)	Types of phthalate esters migrated	Exposure temperature (ambient, refrigeration, heating, pasteu -rization, etc.)	Contact duration (hours, days, months)	Concentration of migrated phthalate esters (DEHP, DBP, BBP, etc.)
Bottled water (21 brands, China)[34]	PET, HDPE	Plastic bottles and caps	DBP, DIBP, DMP, DEHP, DEP, BBP, DnOP, DNP	60 °C (10 d); room temp storage	10 days (test)	DBP: up to 1165.3 ng/L; DEHP: 8.24–178.31 ng/L; DEP: 858.72 ng/L; BBP <LOQ–0.69 ng/L
Bottled water (12 brands, Saudi Arabia + imports)[26]	PET, HDPE	Plastic bottles	DMP, DEP, DiPP, DiBP, DnBP, DEHP	25 °C DI-SPME extraction	Not defined (direct analysis)	DMP:ND–44.3; DEP:ND–48.4; DiBP: 25.3–63.5; DnBP: 9.1–112.2; DEHP: ND–92.8 ng/mL
Sachet drinking water (Ghana)[37]	HDPE	Film sachets (printed/unprinted)	DMP, DEP, DBP, BBP, DEHP	8 °C, 30 °C, 40 °C	Up to 28 days	DMP: 0.27–1.83 µg/L; DEP: 0.55–1.96 µg/L; DBP: ND–2.59 µg/L; BBP: up to 1.03 µg/L; DEHP: <5 µg/L
Bottled water (Chile, still/ sparkling, 4 brands)[7]	PET, HDPE	Plastic bottles (500 mL)	DEP, DBP, DEHP, DOP, DMP, DPP, BBP, DEHA	Room temp (25 ± 4 °C, dark storage)	54–615 days	Brand 1 still: 5.8→24.8 µg/L (DEP/DBP); Brand 1 sparkling: 8.2→16.9 µg/L (DEHP); Brand 4 sparkling: up to 20.6 µg/L (DEHP+DBP)
Drinking water (China)[38]	Not defined	Plastic packaged foods (unspecified)	DBP, BBP, DEHP, DNOP, DIHP, DIDP, DPP	Room temp, optimized MSPE conditions	Extraction within minutes	LODs: 0.29–2.59 µg/kg; LOQs: 0.97–8.63 µg/kg; Recoveries 70–108%

Sample	Material	Container	Phthalates	Conditions	Time	Results
Tap water, barreled water, bottled water (Tianjin, China)[40]	PVC, PC, PET	Pipes, barrels, bottles, disposable cups	BBP, DBP, DEHP	Room temp, boiling, 40–60 °C	Immediate–40 days	Tap water Σ3PAEs: 2.4 µg/L; barrels: 1.5 µg/L; bottles: 1.96 µg/L; DEHP ↑135% after 7 days 60 °C
Mineral water and drinking water (Russia)[42]	PET	PET vs. glass bottles	Phthalates (total quantified)	Refrigerated 2–10 °C	23 days	PET: 190–290 ng/dm³; Glass: ~8120 ng/dm³
Bottled water (Mexico)[44]	PET	Bottles 400–750 mL	DMP, DEP, DBP	40 °C	10 days	PET: DMP 1.1–14.8 mg/kg; DBP 9.3–63.6 mg/kg; DEP 3.1 mg/kg (rare)
Bottled water (Egypt)[8]	PET, HDPE	1.5 L bottles	DEHP, DBP, DEP	4 °C, 25 °C, 40 °C	2 weeks – 6 months	Baseline: DEHP 0.104 µg/L, DBP 0.082 µg/L; After storage: DEHP up to 0.432 µg/L, DBP 0.229 µg/L, DEP 0.062 µg/L
Bottled water (6 brands, Iran)[47]	PET	0.5 L bottles	DBP, DEHP, BBP	–18 °C, 0 °C, 4–8 °C, 25 °C, 40 °C	24 h, 10 d, 30 d, 45 d	DBP:0.079–0.702µg/L;DEHP: 0.217–1.610 µg/L; BBP: <LOD–0.130 µg/L
Bottled mineral water (Ireland)[5]	PET	Bottles (3 brands)	DBP, DEHP	Room temp	Not defined	DBP:0.063–0.068µg/L;DEHP: 1.196–1.685 µg/L
Mineral water (Hungary)[6]	PET	Bottles (0.5–2 L)	DiBP, DBP, BBP, DEHP	22 °C, 60 °C (24–72 h)	Up to 1283 days	Non-carbonated: DiBP<0.20 µg/L; DBP <0.80 µg/L; BBP <0.10 µg/L; DEHP <1.70 µg/L
Drinking water (Portugal)[48]	PET	Bottles (PET, glass), tap water DEHP	DIBP, DnBP,	15–25 °C; 40 °C (EU test)	Market samples; 20 min DI-SPME	PET: DIBP 0.10–1.42 µg/L; DnBP 0.06–1.68 µg/L; DEHP 0.07–0.18 µg/L; Glass: DIBP 1.89 µg/L; DnBP 6.5 µg/L;

| Bottled water (Spain)[4] | PET, PC, HDPE, LDPE, PS | Bottles, caps, septa | 40 °C (UNE-EN ISO 177, UNE-EN 13130); ultrasonic | 10 days; 5–15 min | DMP, DBP, BBP, DEHP (not detected) | Phthalates not detected | DEHP 0.02 µg/L |

Although less represented, other food categories provide complementary insights into the factors influencing migration. Beverages such as juices, sodas, and colas are chemically more complex than water, containing acidity, carbonation, or sugars that can modulate leaching behavior. Isci,+ quantified multiple phthalates including DEHP, DINP, and DIDP in juices, while Isci and Dagdemir,[20] showed that carbonated beverages stored for up to 365 days accumulated higher levels of DEHP, DINP, and DNOP, especially under warm conditions. The effect of external factors such as sunlight was also demonstrated by Massahi *et al.*,[25] who reported that reusing PET bottles and exposing them to outdoor temperatures around 40 °C dramatically enhanced DBP, BBP, and DEHP migration into soft drinks. Milk, accounting for 12.50% of the reviewed studies, exemplifies the susceptibility of lipid-rich matrices, with Lin *et al.*,[21] detecting DEHP, DEP, and DIBP in Chinese milk products and Dobaradaran *et al.*,[41] measuring substantial levels of DEHP and DnOP in Iranian pasteurized milk, both highlighting the influence of fat content on phthalate solubility. Solid and semi-solid matrices were less frequently considered but provide important evidence: Yang *et al.*,[2] documented DBP and DEHP in packaged convenience foods such as beans, meat, and cakes, with cakes showing the highest levels, while Sungur *et al.*,[3] and Rios *et al.*,[49] demonstrated that edible oils favor strong enrichment of DBP, BBP, and DEHP, often at concentrations surpassing those detected in aqueous matrices. Food simulants also contributed significantly to this body of evidence, since they permit controlled experimental comparison; Wang *et al.*,[43] demonstrated that DEHP migration from PVDC films followed a polarity gradient (heptane > ethanol > water), while Yang *et al.*,[45] confirmed that DEHP and BBP migrate preferentially into fatty simulants such as isooctane, underscoring the structural basis of phthalate esters lipophilicity. Finally, a smaller subset of studies explored distilled water as a baseline reference, with Chang *et al.*,[46] reporting trace levels of phthalates under standardized conditions.

Regarding packaging polymers, PET remains the dominant material under scrutiny, which is expected given its global use in bottled water, soft drinks, and dairy packaging. However, several studies have also examined other plastics. For example, PE films were investigated in relation to solid and

convenience foods;[2,45] PVC was assessed in food contact applications,[44] and PVDC was studied under laboratory conditions with simulants.[43] These results confirm that while PET is the most studied due to its extensive application, other polymers are also relevant and contribute to the overall understanding of phthalate migration.
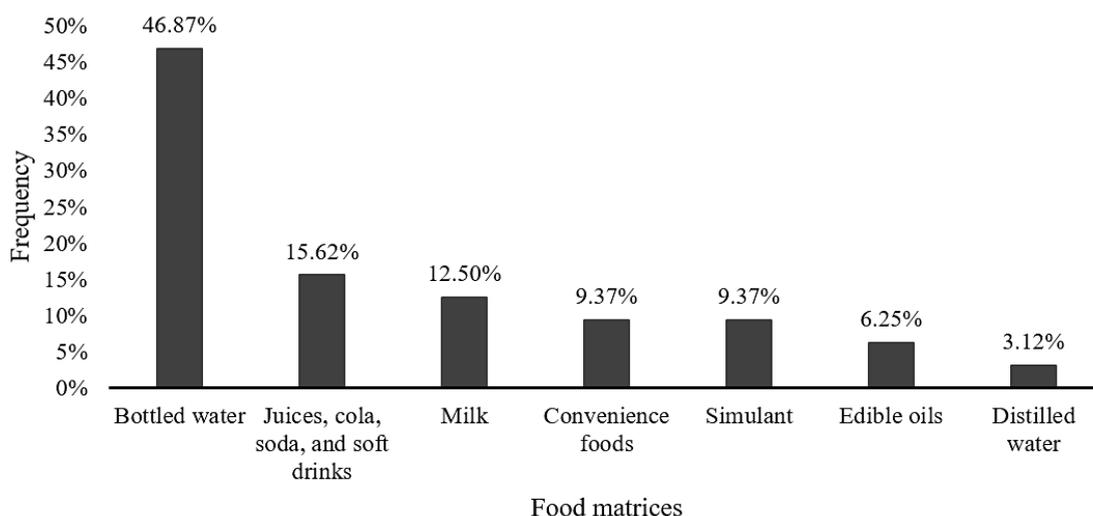

Fig. 5: Distribution of food matrices investigated in phthalate ester migration studies(n=33)

Taken together, these findings show that the occurrence and extent of phthalate esters migration are strongly dependent on the food matrix, the chemical structure of the phthalates, and the polymer type, with aqueous matrices like water being the most frequently investigated, but lipid-rich matrices such as milk and oils providing critical evidence for the higher affinity of lipophilic phthalates such as DEHP, BBP, DINP, and DIDP.

Impact of Ambient, Refrigerated And Heated Conditions on Phthalate Esters Migration

Across the 33 included studies, storage conditions and temperature regimes were systematically identified as critical determinants of phthalate ester (PAE) migration. Under ambient conditions (≈20-25 °C), detectable but generally moderate concentrations of DEHP, DBP, and DEP were consistently reported in bottled water, juices, and milk, with levels increasing gradually over time. Refrigerated storage (≈4 °C) was associated with markedly lower migration rates, although trace amounts of DBP and DEHP were still measurable, particularly after extended durations exceeding several months. In contrast, heated and sunlight-exposed conditions (40-60 °C) consistently led to significant increases in PAE migration, in some cases doubling or tripling baseline concentrations, with DEHP, DBP, and BBP particularly affected. This trend was confirmed across water, milk, juices, and oils, as well as in controlled migration experiments using food simulants.

The predominance of temperature effects on migration was documented across diverse matrices and geographies. In bottled water, Keresztes *et al.*,6 showed that DEHP and DBP accumulated progressively over several years of storage at ≈22 °C, while Guart *et al.*,[4] detected measurable levels of DMP, DBP, and BBP after standard migration tests at 40 °C. Santana *et al.*,[48] similarly reported that bottled waters from Portugal contained higher DBP and DIBP when stored under warmer conditions, underlining the universality of these trends. Zaki and Shoeib,[8] provided further evidence from Egypt, demonstrating that DEHP and DBP increased sharply in waters exposed to 40 °C sunlight for four months, far exceeding baseline levels recorded at room temperature.

Refrigeration emerged as a mitigating factor but not an absolute barrier. Isci and Dagdemir,[20] found that even under 4 °C storage, DINP and DNOP remained detectable in carbonated beverages after 365 days,

suggesting that low temperatures slow but do not prevent migration. This observation is consistent with the findings of Dobaradaran et al.,[41] who recorded increases in DEHP and DnOP in bottled milk stored at 4-5 °C over four days, as well as with Alshehri et al.,[26] who noted that phthalate levels in milk remained measurable under refrigerated distribution conditions.

By contrast, heated storage and accelerated testing produced the highest migration rates. Chang et al.,[46] demonstrated that exposure of PET beverage bottles to 40 °C for 10 days resulted in detectable levels of multiple PAEs, including DIBP and DEHP, with concentrations exceeding those found under ambient conditions. Yang et al.,[45] confirmed this effect using simulants, showing that DEHP and BBP migrated more rapidly into fatty phases such as isooctane at 40-60 °C compared to 4 °C. Similar conclusions were drawn by Wang et al.,[43] whose PVDC migration experiments showed an exponential increase in DEHP leaching as the temperature rose from 25 °C to 80 °C. In practical settings, Massahi et al.,[25] reported that reused PET bottles exposed to direct sunlight at ≈40 °C released significantly higher levels of DBP, BBP, and DEHP into soft drinks compared to bottles stored in the shade, underscoring the synergistic effect of heat and UV exposure.

Other matrices also support these findings. In edible oils, Sungur et al.,[3] reported DBP and BBP concentrations ranging from 0.049 to 2.055 mg/L depending on storage, with higher values in PET bottles under room and warm conditions compared to glass or tinplate. Rios et al.,[49] observed that olive oils stored in PET at ambient and slightly elevated temperatures accumulated DEHP up to 840 µg/kg, significantly higher than in glass bottles. In convenience foods, Yang et al.,[2] demonstrated that DBP and DEHP increased in packaged cakes and meat products stored at room temperature, with higher levels in fat-rich foods after longer storage.

Taken together, these studies converge on a consistent conclusion: temperature is the primary factor controlling the migration of phthalate esters from plastic packaging into food and beverages. While ambient storage already permits measurable migration, refrigeration only slows the process, and heating or sun exposure dramatically accelerates

it. This behavior reflects both the increased mobility of polymer chains and the greater solubility of lipophilic phthalates (such as DEHP, BBP, DINP, and DIDP) at elevated temperatures, as repeatedly demonstrated in bottled water,[6,8,48] milk,[22,32,41] juices and sodas,[20,25,33,35] oils,[3,49] and simulants.[43,45,46]

Effect of Storage Time on Phthalate Esters Release

The reviewed studies consistently indicate that storage duration is a key determinant of phthalate ester (PAE) migration from plastic packaging into food and beverages. Short-term experiments (days to weeks) revealed initial release phases where DBP, DEHP, and BBP were detectable at low concentrations. Intermediate-term storage (1-6 months) was associated with a progressive increase in phthalate concentrations, particularly in bottled waters, juices, and milk. Long-term storage extending beyond six months and up to one year or more resulted in substantial accumulation of heavier phthalates such as DEHP, DINP, DIDP, and DNOP, with levels sometimes approaching or exceeding regulatory thresholds. Overall, the evidence shows a clear time-dependent trend: the longer the storage duration, the higher the release of PAEs across most matrices.

The impact of storage time on PAE release has been documented across multiple food matrices and polymer types. In bottled waters, Keresztes et al.,[6] demonstrated that DEHP and DBP concentrations steadily increased over storage periods extending to 1283 days, with non-carbonated waters showing the most pronounced trends, while carbonated waters contained negligible levels. Similarly, Santana et al.,[48] reported that Portuguese bottled waters stored for extended durations displayed measurable DIBP, DBP, and DEHP, supporting the cumulative effect of time. Zaki and Shoeib,[8] observed progressive increases in DEHP and DBP concentrations in Egyptian bottled waters between 2 weeks and 6 months of storage, with outdoor conditions amplifying the effect.

In beverages other than water, prolonged storage also favored higher migration. Isci and Dagdemir,[20] found that carbonated drinks stored in PET bottles for up to 365 days contained significantly higher concentrations of DINP, DIDP, and DNOP compared to early time points, suggesting that

heavier phthalates accumulate predominantly during long storage. Massahi *et al.*,[25] also showed that phthalate levels in reused PET bottles increased with duration, particularly for DBP, BBP, and DEHP under sunlight exposure, demonstrating that both time and environmental factors synergistically affect migration.

Milk and dairy products further illustrate this effect. Lin *et al.*,[21] measured DEHP, DEP, and DIBP in commercial milk, showing that bound and free fractions of phthalates increased with longer storage. Dobaradaran *et al.*,[41] recorded significant increases in DEHP and DnOP concentrations after just 4 days of refrigerated storage, confirming that even relatively short durations are sufficient to promote measurable release. Alshehri *et al.*,[26] supported these findings by reporting detectable phthalates in milk under distribution conditions, which intensified after extended storage.

Solid and lipid-rich matrices are also sensitive to time. Yang *et al.*,[2] reported higher DBP and DEHP levels in packaged cakes and meats with increasing storage periods, while Sungur *et al.*,[3] showed that edible oils stored in PET bottles accumulated DBP and BBP over time, with concentrations surpassing those observed in oils stored in glass or tinplate. In olive oil, Rios *et al.*,[49] demonstrated a progressive rise in DEHP and DBP in PET containers over 8-12 months, confirming the strong influence of duration in lipid-rich environments.

Evidence from simulant-based studies corroborates these observations. Chang *et al.*,[46] showed detectable increases in multiple PAEs, including DIBP and DEHP, after 10 days of storage at 40 °C, while Yang *et al.*,[45] found that equilibrium concentrations of DEHP and BBP in simulants were reached after several cycles of exposure, reflecting the cumulative impact of repeated contact time. Wang *et al.*,[43] also confirmed time-dependence in PVDC migration experiments, where DEHP leaching increased steadily up to 10 hours.

Taken together, these findings clearly establish that storage time is a critical factor driving PAE release, regardless of matrix or polymer type. Short-term storage may result in low but detectable migration, while medium- and long-term storage substantially increase phthalate concentrations,

especially for lipophilic compounds such as DEHP, DINP, DIDP, and DNOP. This cumulative effect has been consistently demonstrated in bottled water,[6,8,48] beverages,[20,25,33] milk,[21,26,32,41] oils,[3,49] and simulants,[43,45-46] demonstrating a robust and universal time-dependent migration pattern.

The reviewed data also reveal inconsistencies in analytical protocols, particularly in sample pretreatment and quantification methods (GC-MS vs LC-MS/MS), which could partly explain inter-study variability. Some reports quantified only total PAEs, whereas others distinguished between free and bound fractions, resulting in discrepancies of up to several orders of magnitude. This methodological heterogeneity limits direct comparisons but also highlights the urgent need for standardized analytical workflows for PAE monitoring. Harmonization would not only improve data comparability but also enhance the robustness of cumulative exposure assessment.

Variability of Phthalate Esters Migration Concentrationsacross The 33 Studies

Across the 33 included studies, reported concentrations of phthalate esters (PAEs) span several orders of magnitude depending on matrix, polymer, storage regime, and analytical sensitivity. In bottled waters, typical values lie in the ng/L-µg/L range: examples include DBP and DEHP rising from sub-µg/L baselines to 0.2-0.4 µg/L after warm/outdoor storage,[8] increases of DiBP/DBP/DEHP over months to years under ambient storage,[6] low-µg/L totals in Irish and Egyptian brands,[5,26] and brand-/time-dependent spreads up to 25 µg/L total PAEs in Chile after >1 year.[7] Notably, non-detects also occur under standardized conditions4 underscoring method and scenario effects. In juices/soft drinks, concentrations are typically ng/mL (i.e., µg/L), with multi-analyte detections DEP/DBP/DEHP/DINP/DIDP/DNOP) and clear time-temperature responses up to 365 days.[20,35] Milk shows ng/L-ng/g levels linked to lipid content and storage, from detectable DEHP/DBP/DnOP after only a few days[41] to free/bound fractions of DEP/DIBP/DEHP in commercial products,[21] and low-µg/L sums in some surveys.[26,40] Edible oils present higher, mg/L-scale concentrations of DBP/BBP/DEHP in PET vs glass/tinplate[3] and progressive enrichment in olive oil stored in PET over 8-12 months.[49] Convenience foods range to mg/kg, with DEHP up to 5 mg/kg in cakes and measurable

DBP across items,[2] and acidic/fermented vegetables showing µg/L-mg/kg-equivalents with DEHP/DBP variability over time, sunlight and pH.[1,39] Simulant studies confirm matrix effects, from trace ng/kg detections under EU-like tests[46] to mg/kg-level equilibria in fatty simulants,[45] and clear polarity/temperature ordering (heptane, ethanol, water) for DEHP.[43] Additional variability sources include package/cap materials,[26,34] printing/inked films,[37] re-use/sunlight,[25] carbonation,[6] and methodological LOD/LOQ differences.[14,38,46]

Overall, the discussion of phthalate migration patterns shows that food composition plays an equally significant role as temperature and time. Lipid-rich matrices such as oils, milk, and processed foods consistently exhibited higher DEHP and BBP accumulation, reinforcing the lipophilic nature of these plasticizers. By contrast, aqueous matrices such as bottled water remain more stable, though still vulnerable to gradual contamination over prolonged storage. These matrix-specific migration patterns are consistent with diffusion–partitioning models described in polymer science and should be better integrated into predictive exposure models for risk assessment purposes.

Taken together, the wide dispersion of reported PAE concentrations is systematic rather than random, emerging from the joint action of (i) matrix lipophilicity/polarity, (ii) polymer formulation and contact surface (bottle, cap, film, sachet), (iii) time-temperature history (ambient vs refrigerated vs heated/sun-exposed), and (iv) analytical sensitivity and contamination control. Aqueous matrices (waters, distilled water) naturally cluster in the ng/L-low-µg/L domain, but show large between-study spreads driven by storage and climate: accumulations over months/years at 22 °C,[6] steep summer/outdoor slopes at 40 °C,[8] brand- and cap-dependent profiles,[5,34] and totals expanding with long storage.[7] By contrast, lipid-rich or fatty matrices (oils, high-fat foods, milk) upshift the concentration scale by orders of magnitude: mg/L in edible oils packaged in PET,[3] time-dependent DEHP enrichment in olive oil,[49] and measurable free/bound fractions in milk,[21] consistent with the structural hydrophobicity of DEHP, DINP, DIDP and BBP and their preferential partitioning into non-polar phases patterns replicated in simulants where isooctane/heptane, ethanol, water.[43,45] Within beverages, acidity, carbonation and

sugar modulate outcomes: long-term PET storage elevates DINP/DIDP/DNOP and DEHP in juices/colas,[20,35] while re-use and UV/heat further amplify DBP/BBP/DEHP.[25] Solid and fermented foods add pH and processing as drivers, with notable ranges in pickled vegetables under sunlight/acid pH.[1,39] Superimposed on these matrix/condition effects are packaging-specific contributors: higher migration from printed vs unprinted sachets;[37] contributions from closures/caps;[26,34] and polymer diversity beyond PET, including PE, PP, PVC, PVDC in films or multilayers,[43-45] which helps explain outliers and cross-study heterogeneity. Finally, a share of the variability is analytically driven: stringent blanks and low LOD/LOQ yield more non-detects,[4] whereas broader multi-residue methods capture trace-to-low-ng/kg signals.[14,38,46] In sum, variability across the 33 studies follows predictable structure-matrix-process logics: hydrophobic PAEs rise with lipid content and temperature/time; aqueous systems remain lower but highly condition-sensitive; and method/packaging specifics (caps, printing, polymer mix) account for much of the remaining dispersion observed across the literature.[7-8,14,20,25,34,35,37,45]

Methodological Considerations and Limitations
This systematic review was conducted according to the PRISMA 2020 guidelines, which ensured transparency, reproducibility, and a rigorous screening of relevant studies. The multi-database search strategy (ScienceDirect, PubMed, and Scopus) and the clear inclusion/exclusion criteria helped minimize selection bias and provided a broad coverage of the literature published between 2010 and 2025. These methodological elements represent a key strength, as they allowed a structured comparison of reported migration levels for both antimony and phthalate esters across diverse food matrices and packaging materials.

However, some methodological limitations should be acknowledged. Considerable heterogeneity was observed among the included studies in terms of analytical techniques, experimental designs, food matrices, temperature and time conditions, and units of measurement. This variability limited the possibility of performing a quantitative meta-analysis or establishing unified migration trends across datasets. In addition, certain studies lacked detailed information about polymer composition or storage parameters, which may introduce uncertainty in

cross-study comparisons.

To address these constraints, the discussion of influencing factors was intentionally qualitative, focusing on identifying consistent patterns and determining the main parameters driving migration. Future reviews could build on this work by applying harmonized data extraction templates, standardized test protocols, and quantitative meta-analytical tools to enable more robust statistical synthesis. Despite these limitations, the methodological framework adopted here provides a comprehensive and reliable overview of migration behaviors, offering a solid foundation for future experimental and regulatory studies on food contact materials.

Conclusion

This systematic review demonstrates that antimony (Sb) and phthalate esters (PAEs) are recurrent contaminants migrating from plastic food packaging into various food matrices. Across 45 included studies, Sb migration was primarily documented in PET-bottled waters, with most values remaining below the regulatory threshold of 5 µg/L under ambient storage, but reaching as high as 18.5 µg/L under elevated temperatures or acidic conditions. Phthalate esters were more widely investigated, with 32 studies showing their ubiquitous presence in bottled waters, juices, milk, edible oils, and convenience foods. Concentrations ranged from trace levels in aqueous matrices to mg/L or mg/kg levels in lipid-rich foods such as oils and cakes, with DEHP, DBP, and BBP consistently reported as the most abundant compounds.

The synthesis highlights three key determinants of migration: (i) storage temperature, with significant increases observed above 40-60 °C; (ii) storage duration, with progressive accumulation documented up to more than one year; and (iii) food matrix composition, with acidic and fatty products showing enhanced leaching. Although most results fall within current specific migration limits (SMLs), multiple exceedances were observed under stress scenarios, raising concerns for real-life practices such as prolonged storage, re-use of PET bottles, or exposure to sunlight.

Overall, these findings underscore the need for stricter monitoring of both Sb and PAEs, particularly in non-aqueous foods, as well as harmonized protocols for migration testing. Further research is required to address combined exposures, investigate underexplored polymers beyond PET, and integrate toxicological bioassays to refine consumer risk assessment.

Conflict of Interest
The authors do not have any conflict of interest.

Data Availability Statement
Data will be made available on request.

Ethics Statement
This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement
This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration
This research does not involve any clinical trials.

Permission to Reproduce Material from Other Sources
Not Applicable.

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