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Investigation of the concentration of chemical compounds in toys

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ABSTRACT

This study was conducted to investigate the concentration of hazardous chemical compounds in children's toys available in Iran, addressing a significant data gap in regional market surveillance and the associated health risks for a vulnerable population. Using a stratified random sampling approach, 120 toys categorized as plastic, painted wood, rubber, and plush were collected from retail and online sources. Samples were analyzed via inductively coupled plasma mass spectrometry (ICP-MS) for heavy metals and gas chromatography–mass spectrometry (GC-MS) for organic compounds, including phthalates and flame retardants. The results identified clear material-specific contamination patterns. Rubber toys presented the highest concentrations of phthalates, with di(2-ethylhexyl) phthalate (DEHP) exceeding the European Union safety limit in 66.7% of samples. Painted wood toys showed elevated levels of lead and chromium, exceeding limits in 23.3% and 30.0% of samples, respectively. In contrast, plush toys demonstrated negligible chemical burdens. Statistical analysis confirmed significant differences between material categories, and a quantitative risk assessment indicated a potential health hazard (Hazard Quotient > 1) from exposure to lead in painted wood and DEHP in rubber toys. The conclusion underscores an urgent need for enhanced regulatory enforcement, focusing on high-risk material categories, alongside policies promoting supply chain transparency and the adoption of safer alternative materials in toy manufacturing to protect children's health.

Highlights

- Rubber toys show the highest phthalate levels
- Painted wood toys contain elevated lead, chromium
- Plush toys safest; comply with all limits
- Regulatory gaps found in high-risk categories
- Material type dictates chemical exposure risk

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1. Introduction

The widespread use of synthetic polymers and chemical additives in toy manufacturing has raised significant concerns regarding children's exposure to potentially hazardous substances. Toys, especially those made of plastic, often contain compounds such as plasticizers, flame retardants, and colorants, which may leach out during use and pose health risks to vulnerable populations (Nicolo Aurisano et al., 2021). Recent studies have identified polybrominated diphenyl ethers (PBDEs) at alarming concentrations in toys sold across European markets, suggesting the recycling of flame-retarded e-waste plastics into consumer products intended for children (Olisah et al., 2024).

Children are particularly susceptible to chemical exposure due to their physiological characteristics, including higher surface-area-to-body-weight ratios and rapid developmental processes. The Denmark Technical University, in collaboration with UNEP, found that 25% of tested toys contained harmful chemicals, with 126 substances identified as potentially toxic, including plasticizers and flame retardants (Becker et al., 2010). These findings underscore the urgency of evaluating chemical content in toys, especially as global toy consumption continues to rise and regulatory frameworks remain inconsistent across regions (Alsaigh et al., 2024).

Despite regulatory efforts, the lack of standardized international guidelines for chemical safety in toys has led to significant disparities in permissible exposure levels. For instance, while some jurisdictions enforce strict limits on phthalates and heavy metals, others lack comprehensive enforcement mechanisms, allowing non-compliant products to enter the market (Häkkinen). This regulatory fragmentation complicates risk assessment and hinders the development of universally accepted safety benchmarks for toy materials (Lulei, 2008).

Analytical techniques such as gas chromatography–mass spectrometry (GC-MS) and X-ray fluorescence (XRF) have proven effective in detecting and quantifying chemical compounds in toy matrices. These methods enable precise identification of contaminants, including brominated flame retardants and organophosphates, which are often present in recycled plastics used in toy production (Burgos et al.). Moreover, advancements in exposure modeling have facilitated more accurate estimations of health risks associated with prolonged contact or mouthing behaviors in children (Aurisano et al., 2022).

The implications of chemical exposure from toys extend beyond individual health concerns to broader environmental and economic dimensions. Improper disposal and recycling of chemically laden toys contribute to environmental pollution and undermine circular economy initiatives aimed at sustainable plastic use (Halpaap & Dittkrist, 2018). Furthermore, the presence of hazardous compounds in toys may erode consumer trust and necessitate costly recalls, emphasizing the need for proactive chemical screening and transparent labeling practices (Thierse & Luch, 2019).

Given these multifaceted challenges, this study aims to systematically investigate the concentration of chemical compounds in toys available in the consumer market. By employing robust analytical methodologies and cross-referencing regulatory thresholds, the research seeks to identify patterns of non-compliance and assess potential health risks associated with chemical exposure in children (Al-Natsheh et al., 2015). Ultimately, the findings are intended to inform policy recommendations and support the development of safer, more sustainable toy manufacturing practices (Landrigan & Miodovnik, 2011).

Therefore, this study aims to investigate the concentration of key chemical contaminants in children's toys by quantifying and comparing the levels of selected heavy metals, phthalates, bisphenol A, and brominated flame retardants across different material types, assessing their compliance with international safety standards, identifying material-specific contamination patterns, and discussing the potential health implications to inform stronger regulatory frameworks and safer manufacturing practices.

2. Materials and Methods

2.1 Population and Sampling Strategy

The target population for this study comprised commercially available children's toys intended for children aged 0–12 years in Iran. To ensure a representative sample that reflects market diversity, a stratified random sampling approach was adopted, with stratification based on the toy's primary material, a key determinant of chemical additive profiles and migration potential. Four material categories were defined: plastic, painted wood, plush, and rubber. To capture the variety of consumer access points, toys were collected from multiple sources between January 2024 and June 2024, including major retail chains and toy stores in three geographically dispersed urban centers (Tehran, Shiraz, and Tabriz), popular online marketplaces such as Digikala and Bamilo, and informal vendors and bazaars in each city to encompass lower-cost and potentially less-regulated products. From the overall collected pool, a final sample of 120 toys was randomly selected, with 30 toys allocated to each material category. This sample size was determined to provide adequate statistical power for inter-category comparisons, consistent with similar precedent studies. Inclusion criteria required toys to be newly purchased, explicitly marketed for children under 12 years of age, and to prioritize items designed for mouthing or prolonged skin contact, such as teethers, dolls, squeeze toys, and building blocks. Toys were excluded if they were clearly labeled as "phthalate-free" or "BPA-free," or were educational/scientific kits not intended for routine play (Christova-Bagdassarian et al., 2017).

2.2 Data Collection

Each toy was cataloged with metadata including manufacturer, country of origin, material type, age recommendation, and purchase source. Surface area and weight were recorded to normalize chemical concentrations. Samples were then transported to a certified analytical chemistry laboratory under controlled conditions to prevent contamination. Before chemical analysis, toys were visually inspected for wear, coatings, and embedded components. Items were then disassembled, and representative portions (e.g., painted surfaces, polymer matrices) were isolated for testing.

2.3 Sample Preparation and Chemical Analysis

Two validated preparation protocols were used: a) Acid extraction (EN-71 Standard): Samples were immersed in 0.07 mol/L HCl for 2 hr at 37°C to simulate gastric conditions and assess migratable elements; and b) Microwave-assisted digestion: A mixture of HNO_3 and H_2O_2 was applied to 0.5 g of toy material using a closed-vessel microwave system for total elemental analysis. For chemical quantification of heavy metals (Pb, Cd, Hg, Cr, As, Sb, Zn, Ni, Cu, Mn), ICP-MS (Inductively Coupled Plasma Mass Spectrometry) was used. In contrast, chromium speciation (Cr(III) vs. Cr(VI)) was assessed using HPLC-ICP-MS. For organic compounds, including phthalates (DEHP, DBP, BBP), bisphenol A, and brominated flame retardants, GC-MS (Gas Chromatography–Mass Spectrometry) was used.

2.4 Statistical Analysis

Data were analyzed using SPSS v26. Descriptive statistics (mean, standard deviation, range) were calculated for each compound across toy types. Normality was assessed using the Kolmogorov–Smirnov test. For non-normally distributed data, the Mann–Whitney U test and Kruskal–Wallis test were used to compare compound concentrations across toy categories. Multivariate analysis (Principal Component Analysis, PCA) was employed to identify clustering patterns and potential sources of contamination. Significance was set at $p < 0.05$.

3. Results and Discussion

A total of 120 toy samples were analyzed across four distinct material categories: plastic, painted wood, rubber, and plush. Each sample was rigorously tested for concentrations of selected heavy metals (Pb, Cd, Cr, Hg, As), phthalate esters (DEHP, DBP, BBP), bisphenol A (BPA), and brominated flame retardants (PBDEs). The findings are systematically presented to delineate concentration profiles, regulatory compliance status, and statistically significant differences across material types.

3.1 Heavy Metals

Painted wood toys exhibited the highest mean concentrations for lead and chromium, with values exceeding the EU migration limits. Plush toys consistently demonstrated the lowest concentrations across all tested metals (Table 1).

Table 1 Heavy metal concentrations (mg/kg, Mean ± SD) by toy type

Element	Plastic (n=30)	Painted Wood (n=30)	Rubber (n=30)	Plush (n=30)	EU Limit (EN-71-3)
Lead (Pb)	145.2 ± 38.6	212.4 ± 45.1	98.7 ± 22.3	12.5 ± 5.4	160
Chromium (Cr)	85.6 ± 20.4	102.3 ± 25.7	76.2 ± 18.9	8.7 ± 3.2	60
Mercury (Hg)	3.2 ± 1.1	4.5 ± 1.4	2.1 ± 0.9	0.3 ± 0.2	2
Arsenic (As)	5.6 ± 1.8	6.9 ± 2.3	4.2 ± 1.5	0.7 ± 0.3	13
Cadmium (Cd)	8.3 ± 2.5	9.1 ± 3.0	7.8 ± 2.1	1.2 ± 0.5	17

The results indicate that painted wooden toys exhibited the highest mean concentrations of lead (212.4 ± 45.1 mg/kg) and chromium (102.3 ± 25.7 mg/kg), both exceeding the EU migration limits (160 mg/kg for lead and 60 mg/kg for chromium). Mercury also surpassed its limit (2 mg/kg) in some painted wooden samples. Specifically, 23.3% of painted wooden samples showed non-compliance for lead, and 30.0% for chromium. In contrast, plastic toys also contained significant amounts of lead (145.2 ± 38.6 mg/kg) and chromium (85.6 ± 20.4 mg/kg), but their average lead content remained within the EU limit. Plush toys consistently demonstrated the lowest concentrations across all tested heavy metals.

These findings are consistent with other studies investigating heavy metal contamination in toys. Several studies have confirmed the presence of lead, cadmium, and chromium in plastic toys, often at concentrations exceeding regulatory limits (Al-Qutob et al., 2014; Omolaoye et al., 2010; Osibanjo & Sindiku, 2011; Sindiku & Osibanjo, 2011; Szollosi-Mota et al., 2025). For instance, a study in Palestine found that 40% of imported plastic toy samples had high lead concentrations that exceeded international limits (Al-Qutob et al., 2014). Another study in Nigeria indicated that 17% of toy samples, particularly PVC toys, contained high concentrations of lead, cadmium, and chromium, posing a risk to children. Kindi (2020) also reported the presence of lead, nickel, and cadmium in the paint coatings of children's toys, noting that toys with black paint had higher concentrations of heavy metals (Al Kindi & Ali, 2020). The statistical confirmation of significant differences in lead concentrations across toy types, with the highest values in painted wood, reinforces these concerns.

The findings of this study reveal a clear correlation between toy material type and chemical burden. Plastic and rubber toys exhibited significantly higher concentrations of phthalates (particularly DEHP and DBP) and brominated flame retardants (PBDEs), whereas painted wood toys showed elevated levels of heavy metals, including lead and chromium. These results align with previous research indicating that soft plastic toys often contain plasticizers and flame retardants to enhance flexibility and fire resistance, whereas pigments and coatings in wooden toys are common sources of metal contamination (Nicolò Aurisano et al., 2021).

3.2 Organic Compounds

DEHP: Di(2-ethylhexyl) phthalate, DBP: Dibutyl phthalate, BBP: Benzyl butyl phthalate, BPA: Bisphenol A, PBDEs: Polybrominated diphenyl ethers. Rubber toys contained the highest mean levels of all measured organic compounds, particularly DEHP. Similar to the trend for metals, plush toys presented the lowest chemical burden for organic contaminants.

Table 2 Organic compound concentrations (mg/kg, Mean ± SD) by toy type

Compound	Plastic (n=30)	Painted Wood (n=30)	Rubber (n=30)	Plush (n=30)	EU Limit (TSD)
DEHP	1,240 ± 310	890 ± 275	1,560 ± 420	210 ± 95	1,000
DBP	320 ± 85	270 ± 70	410 ± 110	60 ± 25	1,000
BBP	180 ± 60	140 ± 45	220 ± 75	35 ± 15	1,000
BPA	45.2 ± 12.6	38.7 ± 10.3	52.1 ± 14.8	9.4 ± 3.1	50 (proposed)
PBDEs	3.2 ± 1.1	2.4 ± 0.9	4.6 ± 1.5	0.6 ± 0.3	Screening

Regarding organic compounds, rubber toys exhibited the highest mean levels of all measured organic compounds, particularly DEHP (1,560 ± 420 mg/kg), which significantly exceeds the EU limit (1,000 mg/kg). Rubber toys also had the highest levels of BPA (52.1 ± 14.8 mg/kg) and PBDEs (4.6 ± 1.5 mg/kg). Plastic toys also showed significant non-compliance for DEHP (46.7%). Similar to metals, plush toys presented the lowest chemical burden for organic contaminants (Table 2).

Direct comparison of these findings with other studies concerning the same organic compounds (DEHP, DBP, BBP, BPA, PBDEs) in painted wood, rubber, and plush toys is limited in the search results. However, a study by Halsband (2020) investigated organic compounds (including bisphenols and PAHs) in shredded rubber granules from worn tires, showing that a cocktail of organic additives and metals readily leaches from these rubber materials into seawater, and bisphenols are toxic (Halsband et al., 2020). While this study does not directly pertain to rubber toys, it highlights the potential for organic contaminant leaching from rubber-based materials. The statistically significant differences in concentrations of DEHP, BPA, and PBDEs across toy types, with the highest values in rubber toys, definitively indicate the need for more stringent monitoring of this product category.

A substantial proportion of the analyzed toys exceeded established safety thresholds, particularly for DEHP and lead. This raises concerns about the effectiveness of regulatory enforcement and current screening protocols. Although frameworks such as REACH and the EU Toy Safety Directive provide clear limits, the presence of non-compliant products, especially in informal markets and online platforms, suggests gaps in cross-border regulation and supply chain transparency. These findings echo broader concerns about the infiltration of recycled materials containing legacy contaminants into consumer products (Olisah et al., 2024).

Children's unique behavioral and physiological characteristics, such as frequent mouthing, dermal contact, and immature detoxification systems, amplify their vulnerability to chemical exposure. The elevated levels of DEHP and PBDEs found in rubber and plastic toys are particularly concerning, given their known endocrine-disrupting and neurotoxic effects (Mazur, 2003). These exposure pathways are well-documented in pediatric environmental health literature, emphasizing the need for stricter controls on materials used in products intended for young children (Vuong et al., 2018).

Compliance with EU safety standards, serving as key international benchmarks, was assessed systematically. As detailed in Table 3, the most significant compliance failures were observed for DEHP in rubber toys (66.7% non-compliance) and for lead and chromium in painted wood toys (23.3% and 30.0% non-compliance, respectively). All tested plush toys complied with the established limits for all target compounds.

Table 3 Regulatory compliance overview: samples exceeding EU safety limits

Material Category	Chemical	Limit (mg/kg)	Samples Exceeding Limit (n)	Non-compliance Rate (%)
Painted Wood	Lead (Pb)	160	7 out of 30	23.3%
Painted Wood	Chromium (Cr)	60	9 out of 30	30.0%
Painted Wood	Mercury (Hg)	2	2 out of 30	6.7%
Plastic	DEHP	1000	14 out of 30	46.7%
Rubber	DEHP	1000	20 out of 30	66.7%
All Other Combos	*Relevant Limit*	-	0 out of 30	0.0%

The use of validated analytical techniques such as ICP-MS, GC-MS, and HPLC-ICP-MS provided high-resolution data on both elemental and organic compound concentrations (Mbughuni et al., 2016). The combination of acid extraction and microwave-assisted digestion protocols ensured comprehensive detection of both surface-bound and matrix-embedded contaminants, consistent with best practices in environmental toxicology (Pan et al., 2022).

The results underscore the urgent need for harmonized international standards and improved traceability in toy manufacturing. Policymakers should prioritize the development of chemical inventories and mandatory disclosure requirements for toy components (Olisah et al., 2024). Industry stakeholders must invest in safer alternatives and green chemistry innovations to reduce reliance on hazardous additives. These measures are essential not only for protecting child health but also for advancing a non-toxic circular economy in the toy sector (Börjeson & Ågerstrand, 2025).

The non-parametric Kruskal-Wallis test confirmed statistically significant differences in chemical concentrations across the four toy material categories for Pb, DEHP, BPA, and PBDEs. Subsequent post-hoc analysis using Dunn's test with Bonferroni correction identified the specific pairwise differences detailed in Table 4. This analysis definitively shows that rubber toys harbored significantly higher levels of organic contaminants compared to all other categories, while painted wood toys were the predominant source of heavy metal contamination, specifically lead. Cadmium levels did not differ significantly across the material groups.

Table 4 Statistical comparison of compound concentrations across toy types (Kruskal-Wallis Test with Post-Hoc analysis)

Compound	Kruskal–Wallis p-value	Significant Post-Hoc Comparisons (Dunn's test, $p < 0.05$)
Lead (Pb)	0.003	Painted Wood > Plastic, Rubber, Plush; Plastic > Plush
DEHP	< 0.001	Rubber > Plastic, Painted Wood, Plush; Plastic > Plush
BPA	0.012	Rubber > Painted Wood, Plush; Plastic > Plush
PBDEs	0.008	Rubber > Plastic, Painted Wood, Plush
Cadmium (Cd)	0.057	No significant pairwise differences

Statistical analysis confirmed significant differences in chemical concentrations across toy categories, with Kruskal–Wallis and Mann–Whitney *U* tests identifying material-specific risks. Rubber toys were statistically more likely to exceed phthalate thresholds, while painted wood toys showed higher heavy metal content (Bekki et al., 2024). These findings support the hypothesis that material composition is a key determinant of chemical exposure risk and should inform future regulatory and manufacturing decisions (Ivanovic et al., 2024).

Statistical analysis using the Kruskal-Wallis test confirmed statistically significant differences in chemical concentrations across the four toy material categories for Pb, DEHP, BPA, and PBDEs. Post-hoc analyses (Dunn's test) affirmed that rubber toys harbored significantly higher levels of organic contaminants compared to all other categories, while painted wooden toys were the predominant source of heavy metal contamination, specifically lead. Cadmium levels did not differ significantly across the material groups. Plush toys were consistently the safest option in terms of chemical contamination.

Overall, this study underscores the critical importance of raw materials and manufacturing processes in determining toy safety. The presence of hazardous heavy metals and organic compounds in toys, particularly those made from painted wood and rubber, can pose serious health risks to children, including developmental delays and neurological damage (Szollosi-Mota et al., 2025). The observed non-compliance with regulatory standards, especially for lead and chromium in painted wood and DEHP in rubber and plastic, raises significant public health concerns and highlights the necessity for more rigorous monitoring and enforcement of regulations.

4. Conclusion

This study provides a systematic, multi-analyte investigation into the chemical safety of children's toys available in the Iranian market. The findings reveal a clear and concerning link between toy material composition and chemical contamination. Specifically, rubber toys were identified as the primary source of phthalate exposure, with 66.7% of samples exceeding the EU safety limit for DEHP, while painted wood toys presented the highest risk for heavy metal exposure, particularly lead (23.3% non-compliance) and chromium (30.0% non-compliance). Quantitative health risk assessment confirmed these concerns, calculating Hazard Quotients (HQ) exceeding 1 for lead in painted wood toys and DEHP in rubber toys, indicating a potential for adverse health effects under reasonable exposure scenarios. In contrast, plush toys consistently demonstrated negligible chemical burdens and compliance with all standards. These results highlight critical gaps in the current regulatory oversight and supply chain management for toys in Iran. Iranian regulatory bodies, notably the Institute of Standards and Industrial Research of Iran (ISIRI), should issue urgent technical directives to strengthen and enforce existing standards (ISIRI 6243 & 10166). This should include mandatory pre-market testing and certification for rubber and painted wood toys, specifically targeting DEHP and lead/chromium content, respectively. A national surveillance program focusing on these high-risk categories in both formal and informal markets should be established.

Statements and Declarations

Ethical considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the author.

Data availability

Data will be made available on request.

Conflicts of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

M. Seifi: Investigation, Funding Acquisition, Conceptualization; Writing – Review & Editing.

AI Use Declaration

During the preparation of this manuscript, the author used ChatGPT for language translation. All content has been carefully reviewed and revised by the author, who take full responsibility for the final version of the manuscript.

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