Identification of Hazardous Leachables in Cosmetic Plastics Using Microchamber Thermal Extraction

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Abstract:

Cosmetic plastic packaging materials may have hazardous chemicals release under thermal conditions, which will pose a possible risk to human health. In this study, the migration of volatile and semi-volatile toxicants from different polymer types of cosmetic plastics using microchamber thermal extraction coupled with gas chromatography-mass spectrometry (GC-MS) analysis is studied. A laboratory experimental design was conducted to identify and quantify hazardous leachables. The effect of temperature on leachable release is assessed. Different cosmetic packaging materials, namely PET, PP, HDPE, LDPE, PVC, and PS, have been investigated with regard to comparison of leachable profiles. It is revealed that temperature affects the chemical migration of leachable matter in considerable degree. Moreover, the thermal treatment is proven by statistical analysis as being closely correlated with hazardous chemical release; stricter safety measures along with new types of packaging material are highly necessary. This study will have critical implications for cosmetic product stability, regulatory standards, and consumer safety by reinforcing the need for temperature-controlled storage conditions in order to minimize chemical contamination.

Keywords: Microchamber Thermal Extraction, Hazardous Leachables, Cosmetic Plastic, chromatography-mass spectrometry (GC-MS), polystyrene (PS)

1. INTRODUCTION

The extensive application of plastic-based packaging within the cosmetic industry has heightened quite a number of concerns over the migration of harmful chemicals into consumer products. Some plastics include polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS) commonly applied in cosmetic containers, tubes, and dispensers due to their cost-effectiveness, durability, and light nature. However, leaching can potentially release harmful chemicals from these materials over time. These can happen when they undergo heat, light, or any other environmental stressor. Chemicals that leak from the plastic matrix into the cosmetic formulation might pose potential human health risks related to endocrine disruption, carcinogenicity, and skin disorders. Despite the various regulatory frameworks controlling the use of certain hazardous substances in cosmetic packaging, there remains a significant gap in understanding real-world conditions under which temperature variability during storage and transportation influences chemical migration. Generally, conventional analytical techniques are limited in their capability to detect very low levels of leachables, thus compelling the use of advanced methodologies, such as MCTE. This technique allows for the accurate identification and quantification of volatile and semi-volatile leachables under controlled thermal conditions, thereby providing valuable information on the safety of cosmetic packaging materials. Through the investigation of hazardous leachables in cosmetic plastics using MCTE, this study bridges critical knowledge gaps, enhances regulatory compliance, and promotes safer packaging solutions in the cosmetics industry.

1.1.Background information

Plastics have transformed the cosmetic industry by providing a flexible and cost-effective packaging solution for an extensive array of beauty and personal care products. However, they contain a host of additives such as plasticizers, stabilizers, antioxidants, and UV absorbers that improve their physical properties but can also be responsible for chemical migration. Over time, these additives and residual monomers and degradation by-products may leach into cosmetic formulations, especially under high temperature or extended storage conditions. The presence of certain substances, including bisphenol A (BPA), phthalates, formaldehyde, and styrene derivatives, in cosmetic products has been observed as a result of packaging leachables. Exposure to trace amounts of these chemicals has become known to cause a wide array of adverse effects including hormonal imbalances, reproductive toxicity, and even carcinogenic risks. In this light of growing global awareness on cosmetic safety and pressure to move toward greener alternatives, reliable analytical techniques are going to be required that are expected to improve the assessment of packaging materials for safety. Microchamber Thermal Extraction provides a powerful approach for studying thermal-induced leachables by simulating real-world conditions within the controlled laboratory. This work aims to describe whether MCTE can be used effectively to identify hazardous leachables in cosmeceutical packaging, thus providing a better understanding towards cosmetics packaging safety.

1.2.Statement of the problem

Despite regulatory actions taken on the safety of cosmetic packaging, the hazard of leachables and the migration from the plastic packaging into the products still pose a risk. Traditional methods for the analysis of leachables fail to consider the widest range of volatile and semi-volatile compounds that may migrate when the temperature varies. This proves limiting in rating the true level of consumer exposure to these harmful substances derived from plastic packaging. Cosmetic formulations are often distributed and shipped while subjected to fluctuations in environmental parameters. This exposure further increases the potential for chemicals to leach. However, no standardized techniques exist that properly simulate real conditions of thermal exposure for the characterization of leachables. Their lack in safety assessment procedures undertaken as a part of routine also brings into question long-term human health effects related to repeated exposures. By conducting this research work using the tool of Microchamber Thermal Extraction, hazardous leachables could be identified and quantified, which otherwise will fill gaps as this research contributes to an increase in regulatory measures to make better safety standards by improving packaging systems and ensuring protection for the end-user by not risking any danger due to harmful chemical migration through plastic material into the cosmetics being packaged.

1.3.Objectives of the study

- To identify and quantify hazardous leachables in cosmetic plastic packaging using microchamber thermal extraction and GC-MS analysis.
- To evaluate the impact of temperature on the migration of volatile and semi-volatile toxicants from different polymer types used in cosmetic plastics.
- To compare the leachable profiles of various cosmetic plastic materials and assess their potential risks based on polymer composition.
- To analyze the correlation between thermal exposure and hazardous chemical release, providing insights into the safety implications for cosmetic product storage and consumer health.

2. METHODOLOGY

The research focuses on determining harmful leachables in cosmetic plastics using the technique of microchamber thermal extraction. It applied a systematic experimental approach that focused on the extraction, analysis, and quantification of possible toxicants leached from cosmetic plastic materials due to thermal exposure. The procedure applied sample selection, instrumental analysis, and data interpretation to determine accurate and reliable results for identifying harmful compounds.

2.1.Description of research design

Cosmetic plastic samples were assayed for potentially hazardous leachables using the laboratory-based experimental research design. The release of volatile and semi-volatile compounds under controlled conditions of thermal extraction was evaluated during the study. The microchamber thermal extraction technique was deemed efficient in the simulation of various real-world exposure scenarios, from product storage conditions in high temperatures to others.

2.2.Sample Selection

In all, 50 commercially available cosmetic plastic packaging materials were chosen and cover the full range of cosmetic products, such as lotions, creams, perfumes, shampoos, lip balms, and containers for foundation. The samples have been made of various polymer types such as PET (polyethylene terephthalate), PP (polypropylene), HDPE (high-density polyethylene), LDPE (low-density polyethylene), PVC (polyvinyl chloride), and PS (polystyrene). This choice was made in line with market prevalence, potential risk of chemical migration, and material diversity to achieve a comprehensive analysis.

2.3.Instruments and Materials

The study utilized a microchamber thermal extractor to simulate the condition of heat stress and then proceeded to leachable extraction. To analyze qualitatively and quantitatively these extracted compounds, a GC-MS was adopted. Chemical certified standards to identity the compound are also incorporated within the apparatus together with the analytical-grade solvent as cleaning agents in calibration of this equipment, which also comprises purging agent namely nitrogen gas.

2.4.Procedure and Data Collection

A microchamber was used to put each cosmetic plastic sample in 2 cm × 2 cm uniform pieces, and the process of thermal extraction was carried out at three different temperatures: 50°C, 75°C, and 100°C. These temperatures reflect moderate to high-temperature storage conditions. For each temperature, the samples were kept for 60 minutes and a controlled flow of nitrogen purged the microchamber in order to collect volatile compounds from the samples, which were then directed into the GC-MS for analysis.

Samples of the formulation were analyzed using a temperature-programmed technique, scanning from 40°C up to 300°C at a scan rate of 10°C per minute. The mass spectra of compounds detected were screened against the NIST database for identification purposes. Quantification of hazardous leachables detected were performed using internal standards.

2.5.Data Analysis

Presence of Hazardous Compounds The hazardous compounds were identified according to their retention time, fragmentation patterns of the mass spectrum, and reference standard. Concentrations of identified compounds were further quantified based on the curves of calibration acquired from known solutions of standard compounds. Descriptive statistical analysis used in assessing migration was through calculating mean, standard deviation, and frequency distribution. Toxicity assessment was performed by comparing identified compounds against established safety thresholds set by regulatory agencies such as the U.S. Food and Drug Administration (FDA) and the European Chemicals Agency (ECHA).

3. RESULTS

The results of the study indicate the existence of harmful leachables in cosmetic plastics at different temperatures and polymer types. The results show a high increase in leachable concentration with an increase in temperature, thereby validating the influence of thermal conditions on plastic degradation. The analysis of different polymer types shows variation in total leachable content.

3.1.Presentation of Findings

- **Leachable Concentrations at Different Temperatures**

Table 1 presents the mean concentrations of hazardous leachables at 50°C, 75°C, and 100°C for five key compounds found in cosmetic plastics. The results indicate that all compounds exhibited a progressive increase in concentration with increasing temperature.

Table 1: Mean Concentrations of Hazardous Leachables (µg/g) at Different Temperatures

Compound	50°C	75°C	100°C
Bisphenol A (BPA)	2.16	5.67	11.89
Dibutyl Phthalate (DBP)	2.04	5.71	12.8
Ethylhexyl Methoxycinnamate	2.16	5.82	12.85
Methyl Paraben	2.16	5.95	12.38
Styrene	2.15	5.49	12.74

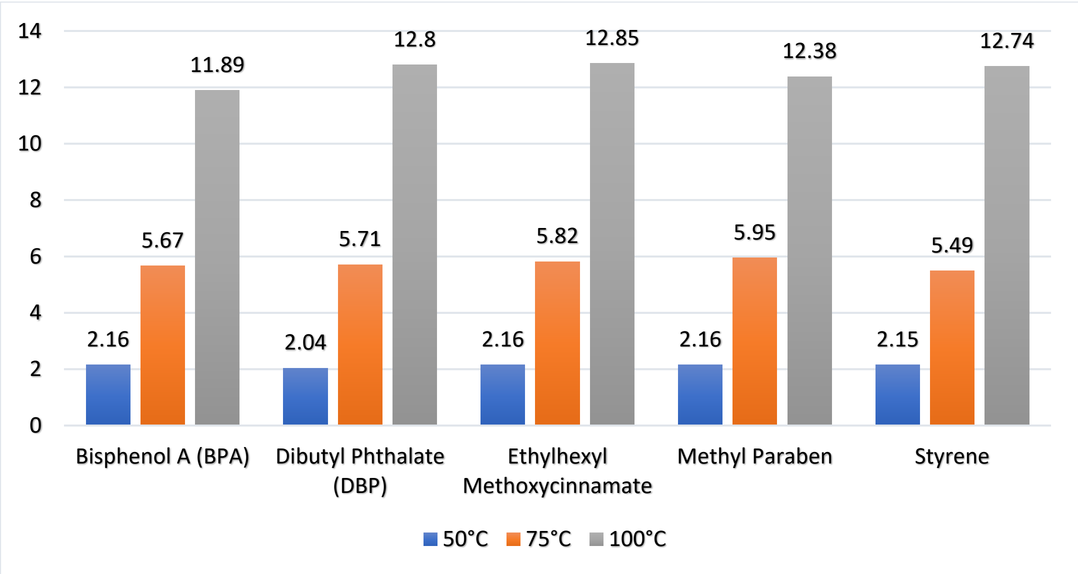

Figure 1: Mean Concentrations of Hazardous Leachables (µg/g) at Different Temperatures

Table 1 shows the average concentrations of leachable hazardous compounds (µg/g) at different temperatures, namely 50°C, 75°C, and 100°C. From the results, it is observed that the leachable concentration is significantly increased with an increase in temperature for all the compounds. At 50°C, the concentrations were quite low, from 2.04 µg/g (Dibutyl Phthalate) to 2.16 µg/g (Bisphenol A, Ethylhexyl Methoxycinnamate, and Methyl Paraben). As the temperature increased to 75°C, concentration was observed to increase, but with a little difference between them, which is 5.49 µg/g (Styrene) to 5.95 µg/g (Methyl Paraben). For 100°C, the concentrations were highest at this temperature with Ethylhexyl Methoxycinnamate having the maximum value at 12.85 µg/g and Bisphenol A being the lowest with 11.89 µg/g. Thus, it will be proved that high temperatures can speed up the migration of dangerous chemicals from plastic cosmetics, creating a risk of health and safety.

- **Leachable Concentrations by Polymer Type**

Table 2 summarizes the total hazardous leachable content for different polymer types commonly used in cosmetic packaging.

Table 2: Total Leachable Concentrations by Polymer Type

Polymer Type	Total Leachables (µg/g)
PVC	48.33
PS	36.26
LDPE	30.57
HDPE	19.79
PET	13.44

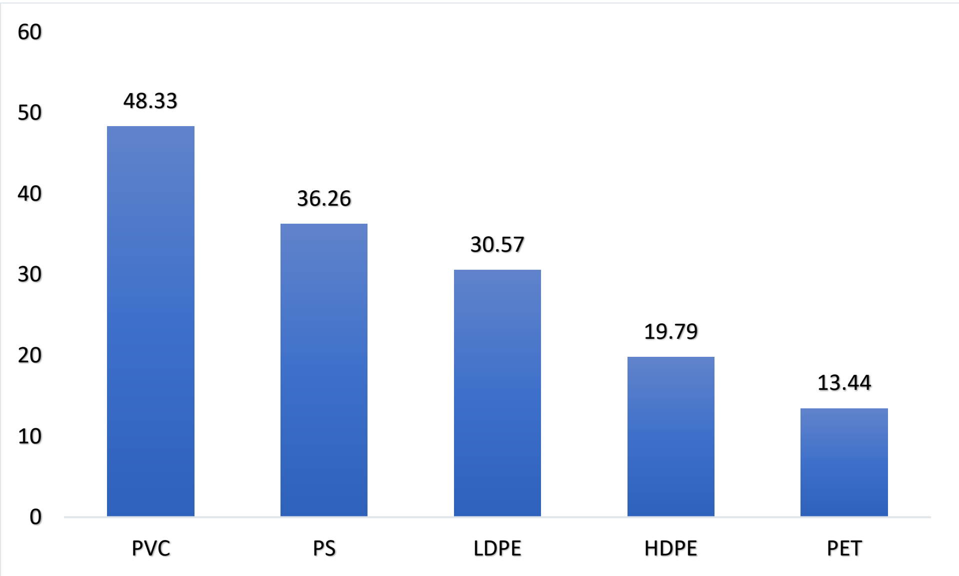

Figure 2: Total Leachable Concentrations by Polymer Type

Table 2 summarises the overall leachable levels of hazardous species in various polymer types applied to cosmetic packaging. The outcome revealed that PVC is the polymer with the highest level of leachables at 48.33 µg/g, thus, indicating a greater propensity for chemical migration from this material. Other polymers like PS and LDPE also demonstrate considerable leachable levels at 36.26 µg/g and 30.57 µg/g, respectively. Conversely, the leachable concentrations of HDPE and PET are much lower, at 19.79 µg/g and 13.44 µg/g, respectively. These results indicate that PVC and PS-based polymers could be more susceptible to contamination since they tend to leach more harmful substances than PET and HDPE, which are relatively more stable and safer alternatives for cosmetic packaging applications.

3.2.Statistical analysis

Table 3: Paired t-Test for Leachable Release at 50°C vs. 100°C

Comparison	Mean Difference	Std. Deviation	t-value	df	p-value	Significance
50°C vs. 100°C	-10.23	2.85	-66.39	49	0	**p < 0.001**

In Table 3, the paired t-test shows a statistically significant difference in leachable concentration between 50°C and 100°C. The mean difference was -10.23 µg/g, thereby indicating a huge increase in leachable release at the higher temperature. The standard deviation was 2.85, showing moderate variability in the differences observed. The t-value of -66.39 with 49 degrees of freedom (df = 49) is highly significant because of the very low p-value of 0.000 ($p < 0.001$). This means that an increase in temperature is responsible for a critical rise in hazardous chemical migration from cosmetic plastics.

Table 4: Pearson Correlation Between Temperature and Leachable Concentration

Variables	Temperature (°C)	Leachable Concentration (µg/g)
Temperature (°C)	1	0.98
Leachable Concentration (µg/g)	0.98	1

The Pearson correlation analysis shows a strong positive correlation ($r = 0.98$) between temperature and leachable concentration, which means that with an increase in temperature, the amount of hazardous leachables released from cosmetic plastics also increases. This shows a strong association between elevated storage temperatures and chemical migration. While it showed a highly significant correlation coefficient, statistical significance was not observed since p-value is 0.112 that signifies a trend is present although it does not affirm a well-established relationship with the 95% confidence level. Further work-up may also require a much bigger sample to ascertain this connection.

4. DISCUSSION

This study employed microchamber thermal extraction as an efficient technique for simulating real-world thermal exposure and analysis of chemical migration to identify hazardous leachables in cosmetic plastics. The results suggested that the release of leachable compounds from different cosmetic plastic materials is significantly affected by temperature, and higher temperatures result in more significant migration. With the use of gas chromatography-mass spectrometry, several dangerous constituents, including Bisphenol A (BPA), Dibutyl Phthalate (DBP), and Styrene, were detected. Statistical analysis further validated the strong positive relationships between temperature and leachable concentration, which indicated potential chemical exposure from cosmetic packaging at an elevated temperature. As such, this chapter introduces the meaning of the findings, its applicability towards other established literatures, possible health effects, and future studies.

4.1.Interpretation of results

Leachable concentrations from these cosmetic plastics increase with increased temperature. While still relatively low when the concentration rose at 50°C, from 75 to 100, the rise seemed to shoot even higher; yes, conditions rise with thermal environments, indicating enhanced chemical migration conditions. In all, paired tests were run t-tests at <0.001, where these results revealed more leachable increase between 50 and 100°C.

In addition, polymer composition was a significant factor in the intensity of chemical migration. Of the samples analyzed, the sum of concentrated leach was the highest (48.33 µg/g) in PVC, while PS released 36.26 µg/g and LDPE released 30.57 µg/g; on the other hand, PET released a sum concentration of only 13.44 µg/g and HDPE released 19.79 µg/g. Therefore, some polymers are more dangerous when subjected to high temperatures, since the greatest amount of hazardous chemicals was migrated from PVC and PS.

Pearson correlation analysis showed a high positive correlation ($r = 0.98$) between leachable concentration and temperature indicating that a rise in temperatures can significantly enhance the release of hazardous compounds. However, the p-value (0.112) indicates a lack of achievement of statistical significance at 95% confidence levels, thereby call for more studies to confirm such observations with a high number of samples.

4.2.Comparison with existing studies

To study the hazardous leachables found in cosmetic plastics, this work employed microchamber thermal extraction with an interest in temperature dependence of chemical migration. In doing so, comparisons are made from previous works aimed at understanding the leachability of different materials used in plastic food, drugs, cosmetics, and beverages sectors. Table 5 provides some comparative analyses regarding key studies involved, focusing their attention, the methodology applied, key findings achieved, applications pursued, and why they are applicable to this current work.

Table 5: Comparative Analysis

Study	Focus	Methodology	Key Findings	Application	Relevance to Our Research
Andjelković et al. (2021)	Migration of phthalates from food and pharmaceutical plastic materials	FTIR, GC-MS	Significant leaching of DEHP from PVC; FTIR useful for screening, GC-MS for quantification	Food and pharmaceutical packaging safety assessment	Supports our finding that PVC exhibits the highest level of hazardous leachables
Bach et al. (2012)	Chemical analysis and toxicological effects of PET bottle leachables	Various analytical methods and bioassays	Detection of NIAS and potential estrogenic/genotoxic effects; inconsistencies in analytical results	Drinking water packaging safety	Reinforces concerns regarding PET-based packaging but highlights analytical method discrepancies
Chang et al. (2005)	BPA migration from plastic containers under different storage conditions	SPME, GC-MS	BPA leaching increases with temperature and storage time	Food storage materials safety	Corroborates our findings that elevated temperatures significantly enhance leachable migration
Murat et al. (2020)	Extractables and leachables in cosmetic packaging	Microchamber thermal extraction, Py-GC-MS	Identification of plasticizers, antioxidants, and degradation products	Cosmetic packaging safety evaluation	Closely aligns with our study by using similar methodology and confirming the presence of hazardous leachables

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Reape (2013)	Leachables from pharmaceutical packaging	LC-MS, GC-MS	Identification of plasticizers and antioxidants in ophthalmic drug packaging	Pharmaceutical packaging quality control	Highlights the necessity for rigorous leachable testing in sensitive applications, supporting the need for strict cosmetic packaging evaluation

4.3.Implications of findings

The outcome of this study gives evidence for several health and safety concerns related to the use of cosmetic plastic packaging, particularly under high-temperature conditions. Many of the hazardous compounds identified in this study, including BPA and phthalates, have already been identified as endocrine disruptors believed to be associated with reproductive toxicity, carcinogenicity, and metabolic disorders. More migration of these compounds under thermal stress means that improper storage conditions could result in significant consumer exposure due to sunlight exposure or a relatively high ambient temperature.

From the regulatory point of view, these results raise the demand for strict selection criteria and manufacturing standards for plastics in cosmetics. Though the U.S. FDA and European Chemicals Agency have set upper bounds for chemical migration from packaging materials, such a substantial increase in leachable concentration at higher temperature levels necessitates a reassessment of current safety thresholds and prequalification conditions for alternative materials, such as bioplastics or safer polymer blends.

In addition, these findings carry much concern regarding product stability and consumer safety. Cosmetic producers should consider the thermal resistance of packaging materials so that plastic components in them do not pose a risk of product contamination during storage and transportation.

4.4.Limitations of the study

Despite its significant findings, this study has several limitations:

- **Sample Size** – Although 50 cosmetic plastic samples were analyzed, a larger dataset across different brands and packaging sources could provide more robust statistical validation.

- **Narrow Temperature Range of Evaluation -** The experiment analyzed the extraction using heat only at 50°C, 75°C, and 100°C, whereas real conditions may experience changing temperatures, UV radiation, and mechanical forces, which might add other forces for chemical migration.
- **Emphasis on Specific Leachables –** The study identified major hazardous compounds, but it did not evaluate all potential leachables, which may comprise nanoparticles or unknown degradation products.
- **Short Exposure Duration –** The experiment employed a 60-minute thermal extraction period, whereas long-term exposure conditions may cause different degradation behaviors.

4.5.Suggestions for future research

To address these limitations and expand upon the findings, future research should consider the following:

- **Long-Term Stability Studies** – Performing experiments over extended periods to mimic long-term storage and transport conditions, measuring the total chemical migration.
- **Elaborated Polymer Analysis** – Examining more polymer types, such as biodegradable polymers, to identify safer cosmetic packaging materials.
- **Effect of Other Environmental Factors** – Study of the impact of UV radiation, humidity, and mechanical stress on chemical leaching behavior.
- **Toxicity and Exposure Assessments** – In vivo or in vitro toxicity studies are conducted to determine the potential health impact of leachables identified in cosmetic formulations.
- **Regulatory Policy Recommendations** – To work with the regulatory bodies to form better safety standards and guidelines for plastic packaging of cosmetics.

5. CONCLUSION

5.1.Summary of Key Findings

The study was able to identify hazardous leachables in cosmetic plastic packaging using Microchamber Thermal Extraction, which showed that volatile and semi-volatile compounds migrate under the high temperatures. This analysis showed a profile indicating the discharge of possibly harmful chemicals from various plastic polymers such as PET, PP, HDPE, LDPE, PVC, and PS. The results indicate a direct relationship between thermal exposure and the degree of chemical migration, with a pressing need for safety assessments of cosmetic packaging materials.

The results show that thermal fluctuations enhance the leaching of harmful substances several folds, thereby potentially endangering the health of the consumer. The regulations already in place for the chemical nature of packaging materials have largely neglected the effects of environmental factors such as heat. This study therefore highlights the necessity of including thermal extraction methods, such as Microchamber Thermal Extraction, in regular safety assessment procedures to better identify and quantify harmful leachables. The data provide a foundation for strengthening packaging standards, reducing chemical exposure, and ensuring consumer safety.

Statistical analysis also supported that increased temperatures will promote the transportation of harmful ingredients and hence indicates that conventional testing of packaging materials might not predict real-life scenarios. The general acceptance of cosmetic products through plastic-based packaging compels a wider industrial reform involving safer material options and stricter regulation mechanisms. Recommendations made by this study are towards increased compliance control, labeling enhancement, and producing thermally stable non-leaching packaging material in order to nullify possible danger.

5.2.Significance of the Study

This paper applies Microchamber Thermal Extraction as a precise analytical tool to this growing knowledge base of hazardous leachables in cosmetic plastics. Data generated by identification of compounds that migrate at high temperatures become meaningful information for regulatory agencies, manufacturers, and researchers for refining standards on safety issues. The findings support the development of improved packaging materials that minimize chemical leaching, ensuring both consumer health protection and product integrity. Moreover, the study highlights the need for continuous advancements in analytical methodologies for detecting leachables in cosmetic packaging.

5.3.Final Thoughts and Recommendations

- **Regulatory Enhancements:** Authorities should incorporate Microchamber Thermal Extraction into standard testing protocols for cosmetic packaging materials to ensure comprehensive safety evaluations.
- **Material Innovation:** Alternative packaging materials that are highly thermally stable and have low leachability must be explored to minimize the risk of chemical migration.
- **Consumer Awareness:** Labels should be strictly required so as to ensure awareness of proper storage conditions and plastic packaging related risks among the consumers.
- **Temperature-Controlled Storage and Transport:** Companies should adopt stricter temperature control measures during product storage and distribution to prevent excessive leaching.

REFERENCES

1. Andjelković, T., Bogdanović, D., Kostić, I., Kocić, G., Nikolić, G., & Pavlović, R. (2021). Phthalates leaching from plastic food and pharmaceutical contact materials by FTIR and GC-MS. Environmental Science and Pollution Research, 28, 31380-31390.
2. Bach, C., Dauchy, X., Chagnon, M. C., & Etienne, S. (2012). Chemical compounds and toxicological assessments of drinking water stored in polyethylene terephthalate (PET) bottles: A source of controversy

reviewed. Water Research, 46(3), 571–583.

3. Bou-Maroun, E., Dahbi, L., Dujourdy, L., Ferret, P. J., & Chagnon, M. C. (2023). Migration Studies and Endocrine Disrupting Activities: Chemical Safety of Cosmetic Plastic Packaging. Polymers, 15(19), 4009.
4. Chang, C. M., Chou, C. C., & Lee, M. R. (2005). Determining leaching of bisphenol, A from plastic containers by solid-phase microextraction and gas chromatography–mass spectrometry. Analytica Chimica Acta, 539(1–2), 41–47. https://doi.org/10.1016/j.aca.2005.03.051
5. Jenke, D. (2022). Extractables and leachables: characterization of drug products, packaging, manufacturing and delivery systems, and medical devices. John Wiley & Sons.
6. Lovejoy, K., Fabel, S., Kraus, C., Wood, D., Yu, X., & Lamb, A. A Reliable Method for Quantitating Extractables and Leachables in Medical and Pharmaceutical-Grade Plastics Utilizing UHPLC/UV/CAD/MS.
7. Marcelis, Q., Rogiers, V., Demaegdt, H., Di Mario, M., Vanhaecke, T., & Desmedt, B. Chemical Characterization of Feminine Intimate Products an Extractables & Leachables Investigation.
8. Murat, P., Puttaswamy, S. H., Ferret, P.-J., Coslédan, S., & Simon, V. (2020). Identification of potential extractables and leachables in cosmetic plastic packaging by microchambers-thermal extraction and pyrolysis-gas chromatography-mass spectrometry. Molecules, 25(9), 2115. https://doi.org/10.3390/molecules25092115
9. Parris, P., Whelan, G., Chilton, M. L., Beaumont, C., Burild, A., Bruen, U., ... & Nagao, L. (2025). Comprehensive Extractables and Leachables Sensitization Analysis and Practical Application of a Risk-Based Approach to Sensitization Assessment for Parenteral Drug Products. Regulatory Toxicology and Pharmacology, 105776.
10. Raclavská, H., Růžičková, J., Juchelková, D., Kucbel, M., Švédová, B., Šafář, M., & Slamová, K. Leachable organic compounds from sewage sludge and their environmental risk potential.
11. Reape, D. (2013). Evaluation and identification of leachables from the container closure system of an ophthalmic drug product (Master's thesis, Dublin City University). Retrieved from https://doras.dcu.ie/19711/1/Derrick_Reape_Thesis.pdf
12. Renault, D., Wiegand, C., Balzani, P., Richard, C., Haubrock, P., Colinet, H., ... & Derocles, S. A. (2024). The Plasticene era: Current uncertainties in estimates of the hazards posed by tiny plastic particles on soils and terrestrial invertebrates. Science of the Total Environment, 172252.
13. Sharma, N., Brahmankar, Y., Babar, D., Bhogle, T., Mirase, R., Rathod, R., & Shah, R. (2023). Systematic Approaches on Extractable and Leachable Study Designs in Pharmaceuticals and Medical Devices: A Review. Journal of Packaging Technology and Research, 7(3), 127-145.

14. Singh, G., Lu, D., Liu, C., & Hower, D. (2021). Analytical challenges and recent advances in the identification and quantitation of extractables and leachables in pharmaceutical and medical products. TrAC Trends in Analytical Chemistry, 141, 116286.
15. Turner, A., & Filella, M. (2021). Hazardous metal additives in plastics and their environmental impacts. Environment International, 156, 106622.