

Recent advancement in Paraben Detection: Journey towards high sensitivity, selectivity, cost-effective AI-driven approaches

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Abstract

Parabens, alkyl or aryl esters of p-hydroxybenzoic acid are commonly used as antimicrobial preservatives in cosmetics, medicines and food products due to their efficacy, stability and cost-effectiveness. Still, there are serious concerns about endocrine disruption, reproductive toxicity, carcinogenic potential and related metabolic and cardiovascular effects mediated through hormone receptor interactions because of their widespread use, effective dermal absorption and systemic bioavailability. Despite their excellent accuracy, conventional detection methods such as colorimetric assays and chromatographic procedures (GC–MS, LC–MS) are constrained by cost, time and operational complexity. The development of sensitive and selective sensor-based platforms, such as electrochemical, optical and nanomaterial-enabled biosensors that can quickly detect in complicated matrices has been the focus of recent developments. Artificial intelligence, enzyme engineering and microfluidic systems integration. Real-time monitoring and forecasting skills are further improved by (AI)-driven analytics. The molecular principles underpinning paraben toxicity are thoroughly covered in this study, which also highlights new biosensing techniques for creating affordable, portable and high-performing detection systems.

Keywords: Paraben Detection, Sensor Technology, Artificial intelligence (AI), Machine learning, Signal amplification, Microfluidics, Lab-on-chip.

Introduction

Paraben(s), the esters of 4-hydroxybenzoic acid, are reported to be the most versatile group of chemical preservatives, used worldwide, due to their non-reactive, inert nature and safety considerations (Alakus et al., 2025). These compounds were assumed to be safe and non-toxic, are reported to be associated with various diseases, including organ toxicity, endocrine disruption, hypertension and cancer to name a few (Arifin et al., 2024). The sudden surge in exploring the underlying mechanisms of Paraben(s) mediated health hazards and the quest to design rapid and sensitive techniques for quantification are indicative of the rapid need to replace it with alternative, safe preservatives (Bao et al., 2025). Conventional detection methods, such as spectrophotometric assays and chromatography-based procedures (GC–MS, LC–MS), provide excellent accuracy but are frequently constrained by prohibitive expenses for operation, time-consuming sample preparation and the need for intricate instruments (Bhatia et al., 2024). The development of affordable and portable sensing techniques, including as electrochemical, optical and nanomaterial-based biosensors, which allow for real-time monitoring with improved sensitivity and selectivity has been the focus of recent advancements (Cetinkaya et al., 2024). Signal amplification and target specificity have been further enhanced by the integration of biologically active nanoparticles (which include metal nanoparticles, carbon nanostructures and molecularly imprinted polymers). In analytical chemistry, artificial intelligence (AI) and machine learning (ML) techniques have lately become groundbreaking innovations that allow for data-driven sensing system efficiency, predictive modeling and recognizing patterns (Lima et al., 2020). In intricate environmental and biological samples, AI-assisted platforms enable better signal processing, fewer false positives and adaptive calibration. Thus, next-generation paraben detection systems that are not only extremely sensitive and selective but also scalable and economically feasible have been rendered possible by the convergence of new materials with AI-driven analytics (Salinas Domínguez et al., 2020). In this review the emergence of paraben detection methods is critically examined, with a focus on recent advances in AI-integrated sensing technologies. It emphasizes significant developments, current constraints and prospects for the creation of reliable, affordable and field-deployable detection systems that are in line with precise and sustainable monitoring frameworks.

Paraben mediated health hazards: Underlying molecular mechanism

In light of potential hazards associated with long-term exposure, parabens which are frequently employed as antimicrobial preservatives in food formulations, medications and personal care products have drawn more attention (Fu et al., 2023). Growing experimental and

epidemiological evidence suggests that parabens can disrupt several cellular and molecular processes, including through endocrine-disrupting activities, despite the fact that they are normally considered safe at controlled concentrations. Due to their structural resemblance to natural estrogens, they can interact with hormone receptors, disrupting physiological signaling networks and causing a variety of metabolic and pathogenic effects (Gibi et al., 2023). Endocrine disruption via estrogen receptor (ER) signaling is one of the main molecular mechanisms underpinning paraben poisoning. Despite having a lesser affinity than endogenous estradiol, parabens can bind to estrogen receptors (ER α and ER β) and activate the transcription of genes that are sensitive to estrogen (Gomes et al., 2023). Hormone-dependent malignancies, fertility and reproductive development may all be impacted by this interaction's alteration of hormonal homeostasis. Longer-chain parabens, including butylparaben and propylparaben, have been shown in studies to have higher estrogenic activity because of their increased lipophilicity and improved receptor binding (Hasan et al., 2025). Exposure to parabens has also been linked to the surplus production of reactive oxygen species (ROS), which causes oxidative stress. Increased ROS levels cause lipid peroxidation, protein oxidation and DNA damage by upsetting the cellular redox balance. Particularly vulnerable to paraben-induced oxidative damage are mitochondria, which can lead to decreased ATP generation, compromised mitochondrial membrane potential and the activation of apoptotic pathways (Ionescu, 2022). Neurotoxicity, metabolic problems and cellular aging have all been linked to this oxidative stress-mediated pathway. Parabens may cause chromosomal instability, DNA strand breakage and disruption of DNA repair processes at the genomic level. Research has shown that exposure to parabens increases the expression of DNA damage indicators such γ -H2AX and activates checkpoint signaling pathways (Kalinina & Pikalova, 2021). Particularly in tissues that are susceptible to hormones, persistent genotoxic stress might encourage mutagenesis and possibly contribute to carcinogenic processes. Crucial intracellular signaling cascades involved in cell survival and proliferation can be modulated by parabens. It has been shown that activation of pathways such MAPK/ERK, PI3K/Akt and NF- κ B results in altered gene expression profiles linked to proliferation, apoptosis and inflammation (Kalita et al., 2023). According to new findings, parabens may potentially have epigenetic effects, such as changes in microRNA expression, DNA methylation and histone modifications. These modifications may have a long-term impact on cellular differentiation, immunological responses and metabolic pathways by influencing gene regulation without changing the underlying DNA sequence (Ko et al., 2024). Therefore, persistent paraben exposure may be linked to developmental and transgenerational health effects through epigenetic alteration.

Parabens may affect immunological and metabolic balance in addition to endocrine and genomic effects (Kruse et al., 2024). Research has shown that exposure to parabens alters lipid metabolism, inflammatory reactions and cytokine production. Increased vulnerability to allergy reactions, metabolic syndrome and problems related to obesity have all been linked to these changes (Lakard et al., 2021). Therefore, a complex interaction of endocrine disruption, oxidative stress, genotoxicity, altered signaling pathways and epigenetic regulation underlies the molecular mechanisms underpinning paraben-mediated health risks. Accurate risk assessment, the emergence of safer preservative substitutes and enhanced monitoring techniques all depend on an understanding of these molecular pathways (Lee et al., 2023).

Types of biosensors for paraben detection

Biosensors for paraben detection comprise a wide range of platforms that are differentiated by their biorecognition components and transduction methods, allowing for sensitive, quick and selective analysis in intricate matrices (Lincho et al., 2021). High sensitivity, mobility and affordability are the main advantages of electrochemical biosensors, which are frequently improved by nanomaterials like graphene, carbon nanotubes, and metal nanoparticles to promote electron transfer and signal amplification. Fluorescence, colorimetric and surface plasmon resonance systems are examples of optical biosensors that provide high-specificity, label-free, real-time detection. Through frequency shifts upon analyte binding, piezoelectric sensors, especially quartz crystal microbalance-based systems allow for mass-sensitive detection (Zargar et al., 2026). Although enzyme-based biosensors use catalytic oxidation of parabens to generate signals, molecularly imprinted polymer (MIP)-based sensors offer strong, synthetic recognition sites with great selectivity and durability. Superior binding affinity and adjustable specificity are provided by newly developed aptamer-based biosensors and their integration with microfluidic lab-on-a-chip platforms enables small, quick and low-volume analysis as shown in table 1. The development of next-generation, high-performance paraben biosensing systems is further advanced by the integration of artificial intelligence, which improves signal processing, pattern identification, and predictive accuracy (Upadhyay et al., 2025).

Table 1: Different types of biosensors for the detection of parabens.

S. No.	Type of Biosensor / Platform	Biological Element / Recognition Mechanism	Detection Technique	Target Paraben(s)	Detection Limit (LOD)	Highlights / Remarks	References

1	Enzyme-based Electrochemical Biosensor (SPE)	Paraben-degrading enzyme (Esterase) immobilized on carbon electrode	Differential Pulse Voltammetry (DPV)	Methylparaben	0.1 μ M	High selectivity, reproducible signal, good stability	(Darbre & Harvey, 2008)
2	MWCNT-modified Screen-Printed Electrode (SPCE)	Enzyme-free, redox-active detection via nanomaterial catalysis	Cyclic Voltammetry (CV), DPV	Methylparaben	0.05 μ M	Enhanced sensitivity due to high conductivity and surface area	(Golden et al., 2005)
3	Molecularly Imprinted Polymer (MIP)-based Sensor	Synthetic polymer imprints mimicking paraben structure	Electrochemical Impedance Spectroscopy (EIS), SWV	Methylparaben	0.03 μ M	Excellent selectivity; reusable and stable	(Bobert et al., 2010)
4	Gold Nanoparticle (AuNP)-Modified Electrode	Physical adsorption of parabens; signal amplification by AuNPs	Square Wave Voltammetry (SWV)	Butyl-, Ethylparaben	0.02 μ M	Superior electron transfer; reliable in cosmetic matrices	(Mitra et al., 2021)
5	Enzyme-Functionalized	Paraben esterase conjugated to GO nanosheet surface	Amperometry	Methylparaben,	0.05 μ M	Fast response	(Azeredo et

	Graphene Oxide (GO) Electrode			Propylparaben		enhanced catalytic activity	al., 2023)
6	Aptamer-based Biosensor	Single-stranded DNA aptamer specific to paraben molecule	Fluorescence Quenching Assay	Methyl-, Butylparaben	10 nM	High affinity; label-free detection	(Liang et al., 2022)
7	Immunosensor	Antibody-antigen interaction using paraben-specific antibodies	SPR / Optical Transduction	Multiple parabens	0.1 μM	High specificity; reusable sensor surface	(Zargar et al., 2026)
8	Nanocomposite-based Electrochemical Sensor (CNC-rGO)	Conductive nanocellulose-graphene hybrid facilitating redox	DPV	Methylparaben	1×10^{-4} M	Green synthesis, eco-friendly platform	(Lakard et al., 2021)
9	Enzyme-free Carbon Nanorod Sensor (C60NRs-NH-Ph/GCE)	Surface electron transfer via nanostructured carbon rods	SWV	Ethylparaben	3.8 nM	Ultra-sensitive; used for cosmetic analysis	(Gomes et al., 2023)

AI-Driven Strategies for High-Sensitivity and Cost-Effective Paraben Detection

A paradigm shift towards the integration of sophisticated sensing materials with artificial intelligence (AI)-enabled analytics has been prompted by the quest for high sensitivity, selectivity and cost-effectiveness in paraben detection (Peinado et al., 2023). Nanostructured biosensors, which take use of increased surface area, catalytic activity and modifiable physicochemical features for ultra-trace detection, are gradually replacing or supplementing traditional analytical platforms, notwithstanding their accuracy (Gaidhani et al., 2024). Target

specificity in complex matrices has been further enhanced by the addition of molecularly designed recognition components, such as aptamers and molecularly imprinted polymers. By facilitating noise reduction, pattern recognition and predictive calibration, artificial intelligence (AI) and machine learning algorithms are simultaneously revolutionizing data capture and interpretation. This reduces false positives and improves analytical resilience. Real-time monitoring and adaptive modifications of sensor performance under changing environmental conditions are made easier by these data-driven methods (Chang et al., 2024). Significantly, scalable, field-deployable detection systems are being made possible by the convergence of low-cost fabrication techniques, portable device topologies and AI-assisted signal processing. The development of next-generation paraben sensing technologies that are not only extremely sensitive and selective but also commercially feasible and appropriate for ongoing environmental and biological surveillance is made possible by this integrated approach (Zhao et al., 2021).

Challenges and Future Prospects

Paraben biosensing technologies have achieved great progress, but there are still a number of important obstacles that prevent them from being widely used. Selectivity is a major issue in complex matrices, where analytical precision is compromised by co-existing interferents and structurally identical phenolic chemicals (Agarwal et al., 2025). Denaturation, leaching and environmental sensitivity continue to limit sensor stability and reproducibility, especially in enzyme-based systems. Furthermore, even though nanomaterial-based sensors increase sensitivity, they frequently enforce problems with scalability, surface fouling and batch-to-batch variability. Inter-laboratory repeatability and regulatory acceptance are further limited by the absence of defined methods and validation frameworks (Pulcastro & Ziv-Gal, 2024). The need for sample pretreatment, short shelf life and challenges with continuous monitoring make it harder the integration of biosensors into practical applications. The emergence of reliable, multipurpose sensing platforms with enhanced antifouling capabilities and long-term stability holds promise for the future (Dasmahapatra et al., 2024). It is anticipated that developments in aptamer engineering and molecularly imprinted polymers would improve specificity and reusability. Miniaturized, fully integrated lab-on-chip systems for quick, on-site detection will be made possible by the convergence of nanotechnology and microfluidics (Witorsch & Thomas, 2010). Additionally, the integration of machine learning and artificial intelligence provides strong tools for predictive analytics, anomaly identification and signal optimization in intricate data sets. Commercialization will require a focus on green synthesis, economical fabrication, and scalable production and regulatory compliance will make it easier

to translate into useful environmental and biomedical monitoring applications (Petric et al., 2021).

Conclusion

Parabens, which are commonly used as effective and inexpensive preservatives, have emerged as compounds of concern due to their widespread environmental presence and potential to cause adverse health effects through endocrine disruption, oxidative stress and interference with hormone-regulated signaling pathways. The crucial necessity for accurate and dependable detection techniques is highlighted by these toxicological ramifications. The development of sophisticated biosensing systems has increased due to the operational constraints of standard analytical methods, despite their high accuracy. These toxicological ramifications highlight how urgently accurate and trustworthy detection methods are needed. Although traditional analytical techniques are highly accurate, their operational constraints have sped up the creation of sophisticated biosensing systems. High sensitivity, selectivity and quick detection have been achieved by a variety of biosensor types, such as electrochemical, optical, piezoelectric, enzyme-based, molecularly imprinted polymer and aptamer-based systems, especially with the use of nanomaterials and miniaturized platforms. Ongoing advancements combining microfluidics, enzyme engineering and artificial intelligence are positioned to overcome current obstacles pertaining to stability, repeatability and real-sample applicability. The combination of next-generation biosensing technologies and mechanistic toxicology insights offers a solid basis for developing affordable, portable and high-performing platforms for real-time monitoring, supporting better risk assessment and regulatory control of paraben exposure.

References

- Agarwal, D., Bhatt, U., & Soni, V. (2025). Ecotoxicological impacts of parabens on flora and fauna. *Npj Emerging Contaminants*, 1(1), 12. <https://doi.org/10.1038/s44454-025-00012-2>
- Alakus, Z., Piskin, E., Budak, F., Kaya, S. I., Cetinkaya, A., & Ozkan, S. A. (2025). Recent developments in electrochemical sensors for the detection and real-time monitoring of non-steroidal anti-inflammatory drugs. *Electrochimica Acta*, 541, 147392. <https://doi.org/10.1016/j.electacta.2025.147392>
- Arifin, N. M., Mhd Noor, E. E., Mohamad, F., & Mohamad, N. (2024). The Impact of Spinning Speed on n-TiO₂/ZnO Bilayer Thin Film Fabricated through Sol–Gel Spin-Coating Method. *Coatings*, 14(1), 73. <https://doi.org/10.3390/coatings14010073>
- Azeredo, D. B. C., de Sousa Anselmo, D., Soares, P., Graceli, J. B., Magliano, D. C., & Miranda-Alves, L. (2023). Environmental Endocrinology: Parabens Hazardous Effects on Hypothalamic–Pituitary–Thyroid Axis. *International Journal of Molecular Sciences*, 24(20), 15246. <https://doi.org/10.3390/ijms242015246>
- Bao, W., Aodeng, G., Ga, L., & Ai, J. (2025). Aptamer-based electrochemical biosensors: Signal transduction mechanisms, application progress, and future trends. *Sensors and Actuators Reports*, 10, 100366. <https://doi.org/10.1016/j.snr.2025.100366>
- Bhatia, D., Paul, S., Acharjee, T., & Ramachairy, S. S. (2024). Biosensors and their widespread impact on human health. *Sensors International*, 5, 100257. <https://doi.org/10.1016/j.sintl.2023.100257>
- Boberg, J., Taxvig, C., Christiansen, S., & Hass, U. (2010). Possible endocrine disrupting effects of parabens and their metabolites. *Reproductive Toxicology*, 30(2), 301–312. <https://doi.org/10.1016/j.reprotox.2010.03.011>
- Cetinkaya, A., Kaya, S. I., & Ozkan, S. A. (2024). A collection of the best practice examples of electroanalytical applications in education: from polarography to sensors. *Journal of Solid State Electrochemistry*, 28(3–4), 869–895. <https://doi.org/10.1007/s10008-023-05637-0>
- Chang, C.-H., Lu, C.-T., Chen, T.-L., Chen, H.-C., Pan, W.-C., Chang, C.-W., Chen, Y.-C., & Yu, Y.-L. (2024). Relationships between bisphenol A and paraben exposure, oxidative stress, and the activity of outer hair cells in the cochlea in children with hearing loss. *Ecotoxicology and Environmental Safety*, 287, 117310. <https://doi.org/10.1016/j.ecoenv.2024.117310>
- Darbre, P. D., & Harvey, P. W. (2008). Paraben esters: review of recent studies of endocrine toxicity, absorption, esterase and human exposure, and discussion of potential human health risks. *Journal of Applied Toxicology*, 28(5), 561–578. <https://doi.org/10.1002/jat.1358>
- Dasmahapatra, A. K., Chatterjee, J., & Tchounwou, P. B. (2024). A systematic review of the toxic potential of parabens in fish. *Frontiers in Toxicology*, 6. <https://doi.org/10.3389/ftox.2024.1399467>

- de Lima, L. F., Pereira, E. A., & Ferreira, M. (2020). Electrochemical sensor for propylparaben using hybrid Layer-by-Layer films composed of gold nanoparticles, poly(ethylene imine) and nickel(II) phthalocyanine tetrasulfonate. *Sensors and Actuators B: Chemical*, 310, 127893. <https://doi.org/10.1016/j.snb.2020.127893>
- Fu, L., Zheng, Y., Li, X., Liu, X., Lin, C.-T., & Karimi-Maleh, H. (2023). Strategies and Applications of Graphene and Its Derivatives-Based Electrochemical Sensors in Cancer Diagnosis. *Molecules*, 28(18), 6719. <https://doi.org/10.3390/molecules28186719>
- Gaidhani, P. M., Chakraborty, S., Ramesh, K., Velayudhaperumal Chellam, P., & van Hullebusch, E. D. (2024). Molecular interactions of paraben family of pollutants with embryonic neuronal proteins of *Danio rerio*: A step ahead in computational toxicity towards adverse outcome pathway. *Chemosphere*, 351, 141155. <https://doi.org/10.1016/j.chemosphere.2024.141155>
- Gibi, C., Liu, C.-H., Anandan, S., & Wu, J. J. (2023). Recent Advances on Electrochemical Sensors for Detection of Contaminants of Emerging Concern (CECs). *Molecules*, 28(23), 7916. <https://doi.org/10.3390/molecules28237916>
- Golden, R., Gandy, J., & Vollmer, G. (2005). A Review of the Endocrine Activity of Parabens and Implications for Potential Risks to Human Health. *Critical Reviews in Toxicology*, 35(5), 435–458. <https://doi.org/10.1080/10408440490920104>
- Gomes, G. C., da Silva, M. K. L., Barreto, F. C., & Cesarino, I. (2023). Electrochemical Sensing Platform Based on Renewable Carbon Modified with Antimony Nanoparticles for Methylparaben Detection in Personal Care Products. *Chemosensors*, 11(2), 141. <https://doi.org/10.3390/chemosensors11020141>
- Hasan, M. Z., Dipti, T. T., Liu, L., Wan, C., Feng, L., & Yang, Z. (2025). Coating Metal–Organic Frameworks (MOFs) and Associated Composites on Electrodes, Thin Film Polymeric Materials, and Glass Surfaces. *Nanomaterials*, 15(15), 1187. <https://doi.org/10.3390/nano15151187>
- Ionescu, R. E. (2022). Use of Cysteamine and Glutaraldehyde Chemicals for Robust Functionalization of Substrates with Protein Biomarkers—An Overview on the Construction of Biosensors with Different Transductions. *Biosensors*, 12(8), 581. <https://doi.org/10.3390/bios12080581>
- Kalinina, E., & Pikalova, E. (2021). Opportunities, Challenges and Prospects for Electrodeposition of Thin-Film Functional Layers in Solid Oxide Fuel Cell Technology. *Materials*, 14(19), 5584. <https://doi.org/10.3390/ma14195584>
- Kalita, N., Gogoi, S., Minter, S. D., & Goswami, P. (2023). Advances in Bioelectrode Design for Developing Electrochemical Biosensors. *ACS Measurement Science Au*, 3(6), 404–433. <https://doi.org/10.1021/acsmeasuresciau.3c00034>
- Ko, C.-H., Tadesse, A. B., & Kabiso, A. C. (2024). Spectrochip-based Calibration Curve Modeling (CCM) for Rapid and Accurate Multiple Analytes Quantification in Urinalysis. *Heliyon*, 10(18), e37722. <https://doi.org/10.1016/j.heliyon.2024.e37722>
- Kruse, J., Wörner, J., Schneider, J., Dörksen, H., & Pein-Hackelbusch, M. (2024). Methods for Estimating the Detection and Quantification Limits of Key Substances in Beer

- Maturation with Electronic Noses. *Sensors*, 24(11), 3520.
<https://doi.org/10.3390/s24113520>
- Lakard, S., Pavel, I.-A., & Lakard, B. (2021). Electrochemical Biosensing of Dopamine Neurotransmitter: A Review. *Biosensors*, 11(6), 179.
<https://doi.org/10.3390/bios11060179>
- Lee, S. J., Cho, J., Lee, B.-H., Hwang, D., & Park, J.-W. (2023). Design and Prediction of Aptamers Assisted by In Silico Methods. *Biomedicines*, 11(2), 356.
<https://doi.org/10.3390/biomedicines11020356>
- Liang, J., Yang, X., Liu, Q. S., Sun, Z., Ren, Z., Wang, X., Zhang, Q., Ren, X., Liu, X., Zhou, Q., & Jiang, G. (2022). Assessment of Thyroid Endocrine Disruption Effects of Parabens Using In Vivo, In Vitro, and In Silico Approaches. *Environmental Science & Technology*, 56(1), 460–469. <https://doi.org/10.1021/acs.est.1c06562>
- Lincho, J., Martins, R. C., & Gomes, J. (2021). Paraben Compounds—Part I: An Overview of Their Characteristics, Detection, and Impacts. *Applied Sciences*, 11(5), 2307.
<https://doi.org/10.3390/app11052307>
- Mitra, P., Chatterjee, S., Paul, N., Ghosh, S., & Das, M. (2021). An Overview of Endocrine Disrupting Chemical Paraben and Search for An Alternative – A Review. *Proceedings of the Zoological Society*, 74(4), 479–493. <https://doi.org/10.1007/s12595-021-00418-x>
- Peinado, F. M., Iribarne-Durán, L. M., & Artacho-Cordón, F. (2023). Human Exposure to Bisphenols, Parabens, and Benzophenones, and Its Relationship with the Inflammatory Response: A Systematic Review. *International Journal of Molecular Sciences*, 24(8), 7325. <https://doi.org/10.3390/ijms24087325>
- Petric, Z., Ružić, J., & Žuntar, I. (2021). The controversies of parabens – an overview nowadays. *Acta Pharmaceutica*, 71(1), 17–32. <https://doi.org/10.2478/acph-2021-0001>
- Pulcastro, H., & Ziv-Gal, A. (2024). Parabens effects on female reproductive health – Review of evidence from epidemiological and rodent-based studies. *Reproductive Toxicology*, 128, 108636. <https://doi.org/10.1016/j.reprotox.2024.108636>
- Salinas Domínguez, R. A., Domínguez Jiménez, M. Á., & Orduña Díaz, A. (2020). Antibody Immobilization in Zinc Oxide Thin Films as an Easy-Handle Strategy for *Escherichia coli* Detection. *ACS Omega*, 5(32), 20473–20480.
<https://doi.org/10.1021/acsomega.0c02583>
- Upadhyay, P., Gauba, P., & Mathur, A. (2025). From Preservative to Environmental and Health Hazards: A Review on Diverse Applications, Health Impacts and Detection Methods of Paraben(s). *Nature Environment and Pollution Technology*, 24(2), B4209.
<https://doi.org/10.46488/NEPT.2025.v24i02.B4209>
- Witorsch, R. J., & Thomas, J. A. (2010). Personal care products and endocrine disruption: A critical review of the literature. *Critical Reviews in Toxicology*, 40(sup3), 1–30.
<https://doi.org/10.3109/10408444.2010.515563>
- Zargar, N., Rasheed, A., Sharma, N., Bashir, Y., & Das, S. (2026). Paraben as an emerging global concern: A comprehensive review on remediation by conventional and advanced

technologies encompassing techno-economic and life cycle assessment. *Journal of Water Process Engineering*, *85*, 109822. <https://doi.org/10.1016/j.jwpe.2026.109822>

Zhao, Y., Liu, Y., Chen, Y., Wu, X., Xiao, Q., Li, C., Li, M., Hu, W., Gu, H., & Lu, S. (2021). Exposure to parabens and associations with oxidative stress in adults from South China. *Science of The Total Environment*, *774*, 144917. <https://doi.org/10.1016/j.scitotenv.2020.144917>