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Impact of Household Chemicals on the Aquatic Environment and Advances in Alternative Technologies

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Abstract:

This review summarizes recent research on the impacts of household chemicals on aquatic environments and the development of technologies for their mitigation. Household chemicals such as pharmaceuticals and personal care products (PPCPs), disinfection by-products, and tire rubber transformation products are increasingly detected in surface water, groundwater, and even drinking water sources, where they persist due to continuous domestic discharge. Once released, these substances follow multiple exposure pathways and exhibit complex hazard mechanisms, including endocrine disruption, oxidative stress, and bioaccumulation, which threaten aquatic organisms and may have long-term consequences for human health. Addressing these challenges requires effective mitigation strategies, and recent advances provide promising options. Physical and chemical treatments, such as activated carbon adsorption, advanced oxidation processes, and membrane separation, achieve high removal efficiency but remain constrained by cost and energy requirements. Biological approaches, including microbial degradation and constructed wetlands, are emerging as sustainable and cost-effective alternatives. In parallel, the design of eco-friendly substitutes, such as biodegradable detergents and natural disinfectants, represents an upstream solution to reduce pollutant input at the source. By integrating knowledge of pollution status, hazard mechanisms, and remediation approaches, this review highlights both the ecological risks and potential management pathways, with the overarching goal of informing future research directions, guiding regulatory development, and safeguarding aquatic ecosystems and water quality under the growing pressure of household chemical contamination.

Keywords: Human health; household chemicals; pharmaceuticals and personal care products.

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1. Introduction

Water is an essential resource for human survival and ecosystem stability, yet global water availability faces severe challenges. Although about 70% of the Earth's surface is covered by water, only 2.5% is freshwater, and most of it is not directly accessible. Currently, nearly 3.6 billion people experience water scarcity for at least one month each year, and this figure may exceed 5 billion by 2050. Agriculture remains the largest water consumer, accounting for nearly 70% of global freshwater withdrawals, while emerging sectors such as data centers and artificial intelligence are adding new pressures to water demand. Combined with the effects of climate change, these trends have intensified the imbalance between water supply and demand, further aggravating risks to water security.

Household chemicals represent an overlooked but increasingly important source of aquatic pollution. Pharmaceuticals and personal care products (PPCPs), disinfection by-products, and additives from consumer goods enter rivers, lakes, and groundwater through wastewater discharge, recreational activities, and stormwater runoff. Their persistence, transformation into toxic by-products, and potential to bioaccumulate pose ecological risks and threaten human health through exposure pathways such as drinking water and food chains. However, existing water treatment systems are often insufficient to remove these contaminants effectively, creating an urgent need for improved understanding and innovative solutions [1]

This study aims to review current knowledge on the environmental impacts of household chemicals in aquatic systems and to evaluate the progress of alternative technologies for their mitigation. By analyzing pollution status, hazard mechanisms, and removal strategies—including physical, chemical, and biological methods—this review highlights both achievements and limitations of existing research. The findings are expected to provide insights for developing safer alternatives, advancing water treatment technologies, and supporting sustainable environmental management practices [2].

2. Literature References

Pharmaceuticals and personal care products (PPCPs) are a major class of emerging contaminants that have attracted wide attention in recent years. They include antibiotics, preservatives, and organic UV filters. Although usually present in trace concentrations in aquatic systems, their continuous discharge creates a "pseudo-persistence" phenomenon. Functional groups such as carboxyl, amino, and aldehyde prolong their retention in the environment, and their non-volatile nature facilitates accumulation in sediments and organisms, thereby transferring through food chains and posing risks to ecological and human health.

PPCPs enter aquatic environments primarily through (i) incompletely treated medical, industrial, and municipal wastewater, and (ii) agricultural runoff, aquaculture, animal husbandry, and recreational activities. Residues have been widely detected in surface water, groundwater, and even drinking water worldwide. Overseas, concentrations range from ng/L to μg/L, with higher levels in municipal effluents; in China, over one hundred types of PPCPs have been detected, with antibiotics at relatively high concentrations, especially in the Pearl and Liaohe River basins [3].

Chloroxylenol, a common antimicrobial, exemplifies these risks. Due to its high chemical stability, it has been shown to cause endocrine disruption, embryonic death, and abnormal development in aquatic organisms, thereby threatening ecosystem balance. Similarly, 6PPD, an antioxidant widely used in tires, reacts with atmospheric ozone to form 6PPD-quinone, which exhibits extreme acute toxicity to juvenile coho salmon ($LC50 \approx 95$ ng/L). This compound has been frequently detected in stormwater runoff in western U.S. cities, often at or above lethal levels.

To address these issues, physical, chemical, and biological treatment technologies have been investigated. Physical methods (e.g., coagulation-flocculation, sedimentation, adsorption, membrane filtration) are simple and low-cost but often show limited PPCP removal efficiency, highly dependent on pollutant properties and water quality. Adsorption performs well for organic pollutants but requires costly regeneration of adsorbents, while reverse osmosis achieves high removal but suffers from fouling and expense.

Chemical methods focus on oxidation or reduction reactions. Oxidants such as potassium permanganate, ferrate, chlorine, chlorine dioxide, and ozone have been studied extensively. Ozone is convenient and effective but selective, and it may produce toxic by-products such as bromate. Advanced oxidation processes (AOPs)—including UV/H_2O_2, O_3/H_2O_2, catalytic ozonation, photocatalysis, and electrochemical methods—generate hydroxyl radicals to achieve broader pollutant degradation, though concerns remain about cost, stability, and secondary pollution.

In addition to removal, the development of environmentally benign substitutes has been explored. For example, 2,6-dichlorobenzoquinone, identified by Hong Kong University of Science and Technology, exhibits 9–22 times greater antimicrobial efficacy than chloroxylenol, rapid hydrolytic degradation in seawater, and significantly reduced developmental toxicity, demonstrating promising substitution potential.

Overall, current studies confirm that household chemicals exert notable ecological and health risks, while treatment technologies and substitutes provide partial solutions. However, challenges remain regarding high costs, incomplete removal, and technical instability, indicating the need for further research and innovation [4].

(1) Insufficient research scope and representativeness

Limited pollutant coverage: Research is concentrated on well-known contaminants such as PPCPs and 6PPD-quinone, while other widely used chemicals (e.g., cosmetic additives, novel surfactants) are understudied.

Regional bias: Data are mainly derived from developed areas and typical basins, with little focus o rural or underdeveloped regions, limiting generalizability.

Temporal limitations: Acute toxicity studies dominate, whereas chronic low-dose effects and long-term ecological impacts remain underexplored [5].

(2) One-sided technical evaluation

Life-cycle neglect: Studies often overlook environmental impacts of alternative technologies across their full life cycle (e.g., energy demand, by-product toxicity).

Weak applicability: Promising laboratory-scale methods (e.g., AOPs) lack evaluation under complex real-world conditions such as high-salinity or organic-rich wastewater.

Economic feasibility: Cost analysis and large-scale applicability are rarely addressed, reducing the practicality of recommendations [6].

(3) Mechanistic and data limitations

Unclear dose–effect relationships: Many studies only report contaminant concentrations without establishing quantitative links to toxicological outcomes.

Neglect of mixture effects: Real-world water systems often involve multiple pollutants with synergistic or antagonistic interactions, which are insufficiently studied.

Unclear degradation mechanisms: Removal efficiencies are reported without identifying degradation pathways or the toxicity of intermediate products [7].

(4) Logical flaws in conclusions

Over-extrapolation: Laboratory results are sometimes generalized to natural ecosystems without accounting for complexity such as hydrodynamics and biodiversity, leading to overstated conclusions.

4.3 Relevance to the current study

Addressing these gaps is highly relevant for advancing research on household chemicals and alternative technologies:

Guiding research focus – Expanding investigations to neglected pollutants, understudied regions, and long-term ecological risks will provide a more complete understanding of contamination.

Improving technical evaluation – Emphasizing life-cycle assessment and real-world adaptability can bridge the gap between laboratory success and engineering application.

Strengthening mechanistic rigor – Clarifying dose–response relationships, mixture effects, and degradation pathways ensures sound conclusions and supports technology optimization.

Informing policy and regulation – Avoiding premature generalizations and considering potential “replacement risks” enables evidence-based policymaking and safeguards against substituting old pollutants with new hazards.

In sum, recognizing these gaps ensures that current research not only advances scientific knowledge but also delivers practical, scalable solutions for mitigating household chemical pollution and protecting aquatic ecosystems [8].

3. Conclusion

This review has provided a comprehensive synthesis of existing studies on the impacts of household chemicals on aquatic environments. Pharmaceuticals and personal care products, disinfection by-products, and tire rubber transformation products have been identified as key pollutants, with well-documented persistence, transformation into toxic derivatives, and significant risks to aquatic organisms and human health.

Research on alternative technologies has demonstrated progress in physical, chemical, and biological treatment methods, as well as in the development of novel substitutes. While these approaches show potential in laboratory and pilot-scale applications, challenges remain in terms of cost, stability, efficiency, and real-world applicability.

Future work should focus on optimizing current treatment technologies, advancing eco-friendly alternatives, and strengthening whole-process management of household chemicals from production to disposal. Addressing these challenges will be crucial to mitigating chemical pollution, protecting aquatic ecosystems, and ensuring sustainable water safety for human populations.

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