Environmental Behaviour and Ecological Risk Assessment of Physical and Chemical Sunscreen Ingredients

Yuxin Lai*

Changsha Zhongjia High School, Changsha, 410000, China

Abstract. Sunscreen ingredients are typical aquatic contaminants of emerging concerns (CECs), with physical (TiO_2/ZnO nanoparticles) and chemical (organic UV filters) types differing in environmental behaviors, yet systematic comparative studies are lacking. This paper systematically reviews relevant studies from 2006 to 2026, comparing their environmental occurrence, fate and ecotoxicity in aquatic ecosystems, and identifying key influencing factors and research gaps. Results show both types are widely detected globally (concentrations linked to anthropogenic activities), with physical nanoparticles tending to accumulate in sediments, whereas chemical filters exist in both dissolved and particulate forms in surface waters. They exhibit distinct fate characteristics and dose-dependent toxicity to aquatic organisms with different mechanisms, and chemical filters pose higher ecological risks in tourist coastal areas while cumulative risks of coexisting ingredients are common. Key research gaps include insufficient mixture toxicity studies, lab-field deviations and the lack of integrated risk assessment systems. This study enriches the knowledge of sunscreen-derived CECs, provides theoretical support for aquatic environmental management and eco-friendly sunscreen development, and proposes priorities for future research on mixture toxicity, lab-field validation and comprehensive risk assessment.

1 Introduction

1.1 Research background

Sunscreen products are widely used worldwide to protect human skin from harmful ultraviolet radiation. Due to their large-scale consumption and frequent use in people's lives, the active substances in sunscreen products continue to be released into water bodies through various pathways, making them typical contaminants of emerging concern (CECs) in aquatic environments. Physical (mineral) sunscreens (primarily TiO_2 and ZnO nanoparticles) and chemical (organic) sunscreens (including benzophenones, cinnamates, etc., as UV filters) differ significantly in their physicochemical properties, resulting in different environmental fates and behaviours after release into aquatic systems [1].

* Corresponding author: l629180996@163.com

Sunscreen active ingredients enter natural waters through several main paths: direct release during recreational activities in coastal and inland water areas, effluent discharged after cosmetic use, and non-point source pollution introduced by tourism facilities at water-rich scenic spots. These compounds have been widely detected in the surface waters, sediments, and aquatic organisms across marine and freshwater systems worldwide. Existing toxicology research has confirmed that the physical and chemical components of sunscreen products all have a certain degree of toxicity to aquatic organisms, including oxidant injury, endocrine disruption, growth inhibition and reproductive toxicity. In addition, the development and application of new sunscreen formulations and advanced UV absorbers have added to the ecological risk of these pollutants on Marine Environment.

Research on the environmental Dynamics, transformation Mechanism and ecotoxicological Effects of sunscreen-derived CECs has moved from qualitative detection in water Samples to a more in-depth stage. However, systematic and comparative evaluations of physical and chemical sunscreen contaminants remain limited in the existing literature. There is an urgent need to explore more about the difference in environmental transport, transformation process and ecological hazard of these two kinds of sunscreen ingredients to support the overall environment-risk management.

1.2 Research problem or question

Although research on sunscreen components as aquatic CECs is increasing, many important research gaps remain; thus, it cannot provide a comprehensive evaluation of their ecological risk and help develop accurate environmental governance approaches at present. The key unaddressed problems are summarised as follows:

1.2.1 Absence of systematic comparative studies

Most of the current research focuses on the environmental behaviour or ecotoxicity of individual sunscreen components, with no unified, all-encompassing comparison among physical and chemical sunscreens. The differences in the Paths of ecological Degradation, Biological Accumulation characteristics and toxic mechanism among these two kinds of contaminants have not been clarified yet, which limits a comprehensive understanding of their ecological risk.

1.2.2 Deficiency in mixture toxicity knowledge

The combined toxicological effects and interactive mechanisms of coexisting physical and chemical sunscreen components, as well as their metabolic transformation products, have yet to be elucidated. In natural water bodies, complex mixtures of sunscreen components often form as a result of the wide application of multi-functional sun-protection products. Notably, some degradation products have a greater biotoxicity than the parent compound; however, most existing studies still primarily examine the individual toxic effects of separate ingredients in combination.

1.2.3 Deviation of laboratory simulation and field application

There are significant differences among substantial lab simulation Results and actual aquatic Environments. Most toxicological and environmental behaviour studies are carried out in laboratory environments, and there is little investigation into how complicated natural factors, such as microorganisms, natural organic matter, hydrodynamics and light conditions, influence the fate and toxicity of sunscreen components. Therefore, laboratory tests cannot be directly used for actual aquatic ecological risk assessment and pollution control in the field.

1.3 Purpose of this study

Objective 1: Systematically summarise and contrast the environmental occurrence, fate and transport characteristics of physical (mineral) and chemical (organic) sunscreen ingredients in water bodies. Objective 2 is to assess the ecotoxicity of these two kinds of sunscreens on different trophic levels of water organisms, such as algae, invertebrates, and fish; Summarise their general toxic mechanism and species sensitivity.

Objective 3: To determine the critical environmental factors that govern the environmental behaviour and biohazards of sunscreen compounds in water bodies.

Objective 4: Synthesise current research results, consolidate knowledge gaps existing in the field of sunscreen-related aquatic CECs, and propose target-based future research directions.

1.4 Significance of this study

1.4.1 Scientific significance

To address the significant deficiency in systematic comparative research on physical and chemical sunscreen contaminants in aquatic environments at present, thereby enriching the knowledge system of sunscreen-derived CECs. It can provide a standardised reference basis for subsequent researches in the field of cosmetics-related water pollution, assisting Multi-disciplinary Integration of environmental science and cosmetology to be realized. In addition, it provides new ideas for the ecological risk evaluation of nanomaterial-based and organic small-molecule contaminants of emerging concern.

1.4.2 Environmental management significance

The results of this study provide practical references and theoretical support for the environmental management authorities to develop targeted monitoring indexes and risk management protocols of Sunscreen-derived aquatic pollutants. The results also provide a basis for classifying and assessing the risks of cosmetic-related aquatic pollutants, guide the optimisation of sunscreen formula design and development of eco-friendly UV filters in the cosmetics industry, and offer technical support for risk management of aquatic ecosystems in tourist-dense coastal and inland areas.

1.5 The framework of this paper

The organisation of this paper is as follows. Section 3 presents the research background, points out deficiencies in existing studies, and describes the main purpose of this study. Section 4 reviews systematically in the existing literature on the environmental occurrence, fate, transformation and ecotoxicity of sunscreen compounds. Section 5 presents the process of literature retrieval, screening and analysis in this review. Section 6 provides the primary outcomes of the literature synthesis, with a focus on comparing the environmental behaviour and toxicological impact of physical and chemical sunscreens. Section 7 is about the research implications, deficiencies in previous studies and future study Directions. The final part is the summary of this review's main conclusions, and all referenced materials are listed in the References section in sequence.

2 Literature review

2.1 Overview of the existing research

Research on sunscreen compounds as aquatic contaminants of emerging concerns (CECs) has increased significantly over the past two decades. A growing number of field investigations and laboratory experiments have examined the environmental behaviour and biological effects of sunscreen ingredients in aquatic systems around the world. Comprehensive summary of the four main aspects covered by the above research contents: environmental occurrence, environmental fate, ecotoxicology and analysis detection techniques.

2.1.1 Environmental occurrence in aquatic systems

Physical UV filters (TiO_2 and ZnO nanoparticles) and chemical UV absorbers (including benzophenone derivatives, benzenesulfonic acid derivatives, cinnamate derivatives, avobenzone, and octocrylene) have been widely found in various water bodies. Contaminants present in the surface water, coastal marine areas and bottom sediments and aquatic organisms in temperate, tropical and other highly visited coastal areas [1, 2].

Physical sunscreens form nanoparticles that tend to accumulate more in the sediments of urban and recreational waters; Chemical UV filters are always found in both dissolved and particulate forms in surface waters [3]. According to relevant research, the Mediterranean coastline, municipal rivers in Southeast Asia, and the coral reef lagoons of Australia all exhibit widespread pollution from sunscreen, which is highly related to local usage intensity and sewage treatment degree [4].

2.1.2 Environmental fate

The environmental behaviour of the physicochemical sunscreens mainly depends on their own physicochemical properties, and there will be different transport, transformation and deposition processes in aquatic ecosystems.

Physical Sunscreen: TiO_2 and ZnO nanoparticles have a low water-solubility. The main influencing factors of their environmental transport are water pH, dissolved organic matter (DOM) concentration, ionic strength; And nanoparticle aggregation and sedimentation are the main fate processes in aqueous systems.

Chemical UV filters: These organic substances have varying degrees of water-solubility; BP-3 and cinnamates have moderate solubility in water, while lipophilic substances like octocrylene are poorly water-soluble and tend to be distributed in particulate or organic phases. The main transformation routes of photodegradation and biodegradation for chemical sunscreens are regulated by light intensity, microbial community composition and water temperature.

2.1.3 Ecotoxicological effects

Physical-chemical UV filters have dose-dependent toxic effects on various trophic levels in the aquatic ecosystem, and their specific toxic modes are associated with their physicochemical properties and molecular structures.

Physical Sunscreen: TiO_2 and ZnO nanoparticles can inhibit algal photosynthesis and growth through induced oxidative stress. Their toxicity is not just size-related; it also involves the dimensions of nanoparticles, surface modification, and aggregation state. For example, some nanoparticles will induce oxidative damage and organ dysfunction to aquatic invertebrates and fish through cellular internalisation and tissue-specific accumulation.

Organic (chemical) sunscreens: Some chemical UV filters can cause oxidative stress, endocrine disruption, and reproductive toxicity to marine invertebrates, such as Daphnia and fish. Some hydrophobic chemical substances can accumulate in aquatic organisms, and there is weak biomagnification of these substances in some simple aquatic food chains; but it's not universal, as other factors influence whether there will be biomagnification.

2.1.4 Analytical detection methods

Analysis of techniques for quantitatively determining the residues of sunscreens in water bodies have have achieved notable results. High-performance liquid chromatography coupled with mass spectrometry (HPLC-MS) is generally employed to detect chemical UV filters, and inductively coupled plasma spectroscopy combined with microcharacterisation techniques has become a standard approach for analysing physical sunscreen nanoparticles. These ways realise trace-level detection of target substances in the water and sediment systems, and standard operating procedures have been established for typical components such as BP-3 and TiO_2. There are still problems such as the precise determination of novel sunscreens and nanoparticles in complex natural environmental samples.

2.2 Gap identification in the existing studies

Despite some research achievements in the field of sunscreen-derived aquatic CECs, there are still four deficiencies hindering comprehensive ecological risk assessment and target regulation.

1. Lack of systematic comparison frameworks.

Most existing research focuses on single types of sunscreen or isolated components, lacking a unified standard system for comparing the environmental behaviour and ecotoxicity of physical and chemical sunscreens under the same conditions. The key environmental persistence, biodegradability and other parameters of these contaminants have not yet been quantitatively determined [5].

2. Lack of knowledge on mixture toxicity and metabolites.

Existing toxicology evaluations mainly focus on single compounds, but complex mixtures of physical and chemical UV filters coexist in nature. The synergistic toxic effects of mixtures and the environmental risks of transformation metabolites (some of which may be more toxic than the parent compound) have not been fully investigated [6].

3. Deviation between laboratory simulations and actual fields.

Most of the environmental fate and toxicity data are derived from controlled laboratory experiments in simple environments. The impact of complex natural environment Factors, such as various Microbial communities, Hydrological dynamics On the behaviour of sunscreens remains unknown; laboratory test data often fail to match actual aquatic conditions [7-10].

4. Lack of integrated risk assessment System.

Existing risk evaluations primarily conduct single-factor or single-component analyses. There is no all-around model that takes into account the co-occurrence of physical and chemical sunscreens, dynamic transformation process and variable environmental factors, which cannot meet the actual requirements of ecological monitoring and CEC regulation [8].

2.3 Research contribution

Based on the existing research of aquatic sunscreens' pollutants, this paper aims to address deficiencies in the relevant literature by systematically synthesising and comparing them. Rather than carry out new empirical tests, this work summarizes and organises data from typical field and laboratory research to assess the environmental behaviour and ecotoxicological effects of physical and chemical sunscreens at the four key aspects listed in Section 4.1.

Using a unified analytical framework to integrate the cross-study results helps determine the extent of consistency or difference in environmental behaviour and toxicity among physical, chemical sunscreens. Aquatic ecosystems, as one of the primary natural environment factors that affect sunscreen behavior; Reveal how it impacts ecological risks.

The findings of this study provide an initial basis for future research on the CECCs in sunscreens, as well as target toxicity mixtures and field validate laboratory data. The comparison and synthesis also provide a standardised reference for interdisciplinary researchers in environmental science and cosmetic engineering, and enhance the accuracy of aquatic ecosystem risk assessment specifically designed for the characteristics of sunscreen pollutants.

3 Results

3.1 Overview of major findings

This part systemically synthesises and compares the environmental behaviour and ecological effects of mineral and organic physical sunscreens in the marine ecosystem based on verified peer-reviewed publications. The findings are organised into four main parts to show their similarities and key differences in the types of sunscreens' contaminant problems.

3.1.1 Environmental occurrence levels and distribution characteristics

Field investigations have shown that physical and chemical sunscreens are widely present in the global marine environment, including surface water, coastal seawater and sediments, and there are different spatial distribution patterns. Physical sunscreen particles (TiO_2, ZnO nanoparticles) mainly accumulate in bottom sediment, whereas chemical UV filters exist in both dissolved and particulate forms in water bodies.

Differences in Detection Frequency and Concentration Range: Across different regions. The concentrations of Recreational Coastal Areas, urban Rivers and near-shore Sea areas that attract tourists are significantly higher than others Remote offshore waters have low or no detected levels. Statistical data from compiled studies have confirmed a high degree of consistency among the detection intensity of sunscreen, local human activity level, recreational activities scale and municipal domestic sewage discharge amount.

3.1.2 Environmental fate characteristics and mainly influencing factors

Physical and chemical sunscreens have different environmental fates in marine ecosystems because they are physically and chemically different, and the environment is also different. Low aqueous solubility makes the main mode of transportation and fate process for physical sunscreens particles agglomeration, gravity settling and sediment adsorption; Its mobility is very sensitive to seawater pH, dissolved organic carbon (DOC) content and ionic strength.

Chemical UV filters have different transformation pathways, and photodegradation and microbial biodegradation are their main forms of degradation. The degradation Kinetics and environmental persistence differ for different compounds: octocrylene has high lipophilicity, strong adsorption to particulate Matter, and a long environmental half-life; The moderately lipophilic filter BP-3 is more likely to undergo photodegradation in nature. The critical environmental Factors affecting their existence include microbial community composition, solar radiation, seawater temperature and dissolved organic matter Levels.

3.1.3 Ecotoxicological comparison of different trophic levels

Toxicological data compiled show that both physical and chemical sunscreens have dose-dependent adverse effects on marine organisms at various trophic levels, including phytoplankton, aquatic invertebrates and fish, and there are different species sensitivities and toxic mechanisms. Physical sunscreens mainly cause oxidative stress and photosynthetic inhibition in phytoplankton, and the toxicity is affected by particle size, surface modification and aggregation state; In vertebrates, these nanoparticles cause tissue accumulation and organ damage due to cellular internalization.

Chemical UV filters can cause endocrine disruption, reproductive impairment and developmental abnormalities in aquatic organisms; Among them, invertebrates and young life stages of fish are more sensitive. Hydrophobic chemical substances have significant bioaccumulation potential in marine organisms, and there is weak evidence of trophic transfer in a simplified food web. Chemical sunscreens have a greater acute toxic effect on sensitive water organisms at environmentally relevant concentrations; Physical Sunscreen poses a risk of chronic toxicity through sedimentation.

3.1.4 Ecological risk assessment results and characteristics

Current ecological risk assessment shows different risk levels of physical and chemical sunscreen pollutants in the global marine environment. Risk quotient (RQ) calculations compiled by various studies have classified chemical UV filters as medium- to high-risk ecologically in high-tourist areas of the coast due to their acute toxicity and frequent occurrence at environmental concentrations.

Most marine environments classify physical sunscreens as having a low to moderate ecological risk, and high risk is mainly associated with sediment-dwelling organisms in heavily polluted recreational areas. Spatial Variations in risk magnitude are mainly due to Differences in the intensity of Sunscreen use, Wastewater treatment efficiency and Local Hydrodynamic Conditions. Most evaluated marine ecosystems show cumulative ecological risks of co-existing physical and chemical sunscreen substances, rather than a single substance's effect.

3.2 Statistical analysis

To combine existing published findings in a systematic way and conduct a qualitative systematic literature review, no new empirical statistical tests are performed. Descriptive statistics were conducted in three dimensions based on the eligible and reviewed papers that met the criteria: (1) temporal changes and publication quantity of studies on physical and chemical sunscreen contaminants from 2006 to 2026; (2) proportionate distribution of research methods (field observation and laboratory simulation) among the included studies; and (3) geographical distribution of aquatic ecological impact studies focused on sunscreen contaminants.

4 Conclusion

This research conducted a systematic literature review and comparison of the environmental behaviour and ecological risk features of chemical and physical sunscreen components in marine environments, and the results are based on an in-depth screening and synthesis of relevant works from 2004 to 2024. Based on the four main thematic Dimensions of environmental distribution, environmental persistence, multi-trophic-level ecotoxicology and ecological risk assessment, combining the collected evidence from previous studies, this work aims to identify the essential common elements and fundamental differences among physical forms (TiO2, ZnO nanoparticles) and chemical forms (benzophenones, cinnamates, etc.) of sunscreen products in aquatic environments, as well as determine the key factors affecting their ecological dispersion and ecological hazards.

The findings show that both physical and chemical sunscreens are widespread pollutants in the world's aquatic ecosystems, and their concentrations are closely related to anthropogenic activities; particularly in densely populated coastal tourist areas and inland freshwater recreational zones. In terms of environmental behaviour, nanoparticles in physical sunscreens have low water solubility and mainly migrate by aggregation, deposition and adsorption; On the other hand, the solubility characteristics of chemical sunscreens are different; Photolysis and microbial metabolism are the main ways of degradation, and their environmental persistence is affected by light intensity, microflora and lipophilicity. In terms of ecological toxicity, aquatic organisms exhibit dose-dependent toxicity at different trophic levels, including algae, invertebrates, and fish, but with varying mechanisms; For example, a physical sunscreen can lead to oxidative stress and cell damage through nanoparticle entrapment and accumulation, and its degree of toxicity is related to factors such as particle size and surface coating; A chemical sunscreen may disrupt the endocrine system, reduce fertility, or promote bioaccumulation because it is lipophilic. Regarding ecological risk, the current threat of sunscreen components in many natural waters is moderate to low, but high-risk zones have emerged at some recreational areas due to excessive use and poor discharge control of sunscreens, and the cumulative hazard of multiple sunscreen chemicals and their metabolites has yet to be studied.

This investigation also addresses some deficiencies in the current research on sunscreen-induced marine pollutants, such as no systematic comparative experiments conducted under the same conditions; insufficient exploration of synergistic toxicity; the disconnect between laboratory results and field situations due to differences; lack of a unified ecological risk assessment system. The comparison analysis of chemical and physical sunscreens in this work constructs a knowledge network among them, thereby determining the main research directions for further detailed studies.

The findings of this study provide a scientific basis for precise environmental governance strategies against sunscreen pollutants; for ecological management agencies, they serve as criteria to build monitoring indexes of sunblock components in water bodies and develop risk response plans for areas abundant in recreational facilities; For the beauty industry, these outcomes offer an upgrade theory to promote research into environmentally friendly ultraviolet absorbers that have less impact on ecosystems.

Sunscreen components, as typical cosmetic-originated aquatic emerging pollutants, have posed a substantial threat to the global aquatic Environment due to their widespread use in sunscreens. Comprehensive comparison of the environmental and ecological behavioural characteristics of both physical and chemical sunscreens in this study aims to enhance the ecotoxicological risk assessment system for such pollutants. Future research should focus on three directions: mixture effects of multiple sunscreen compounds; validation of laboratory findings under field conditions; and development of an integrated risk assessment framework covering not only toxic effects to the ecosystem but also environmental persistence potentialities and endocrine disruption hazards that provides technical support for promoting industry coordination.

References

1. M. Chatzigianni, P. Pavlou, A. Siamidi, M. Vlachou, A. Varvaresou, S. Papageorgiou, Environmental impacts due to the use of sunscreen products: a mini-review. Ecotoxicology **31**, 1331–1345 (2022). https://doi.org/10.1007/s10646-022-02592-w
2. A. Medici, G. Luongo, G. di Fabio, A. Zarrelli, Environmental fate of organic sunscreens during water disinfection processes: formation of degradation by-products and their toxicological profiles. Molecules **27**, 4467 (2022). https://doi.org/10.3390/molecules27144467
3. S. Yuan, J. Huang, X. Jiang, Y. Huang, X. Zhu, Z. Cai, Environmental fate and toxicity of sunscreen-derived inorganic ultraviolet filters in aquatic environments: a review. Nanomaterials **12**, 699 (2022). https://doi.org/10.3390/nano12040699
4. G. Ruiz-Gutiérrez, A. Rodríguez-Romero, A. Tovar-Sánchez, J.R. Viguri, Analysis and modeling of sunscreen ingredients' behavior in an aquatic environment. Oceans **3**, 340–363 (2022). https://doi.org/10.3390/oceans3030024
5. N.J. Wheate, Environmental contamination and potential health impacts on aquatic life from the active chemicals in sunscreen formulations. Aust. J. Chem. **75**, 241–248 (2022). https://doi.org/10.1071/CH21236
6. R. Rajan, Sunscreen challenges: stability, systemic absorption, and environmental concerns, in Sunscreens for Skin of Color (Springer, Singapore, 2024), pp. 283–310. https://doi.org/10.1007/978-981-97-3195-4_11
7. I.B. Miller, S. Pawlowski, M.Y. Kellermann, M. Petersen-Thiery, M. Moeller, S. Nietzer, P.J. Schupp, Toxic effects of UV filters from sunscreens on coral reefs revisited: regulatory aspects for "reef safe" products. Environ. Sci. Eur. **33**, 74 (2021). https://doi.org/10.1186/s12302-021-00515-w
8. S. Nishioka, K. Miyata, Y. Inoue, K. Aoyama, Y. Yoshioka, N. Miura, M. Yamane, H. Honda, T. Takagi, Deciphering mechanisms of UV filter (benzophenone-3)- and high temperature-induced adverse effects in the coral Acropora tenuis. Sci. Total Environ. **954**, 176018 (2024). https://doi.org/10.1016/j.scitotenv.2024.176018
9. K. Fent, A.A. Weston, D. Caminada, Ecotoxicology of human pharmaceuticals. Aquat. Toxicol. **76**, 122–159 (2006). https://doi.org/10.1016/j.aquatox.2005.09.009
10. U.S. EPA, UV filters in sunscreens and aquatic environmental health. U.S. Environmental Protection Agency report (2024)