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Challenges and Prospects of Chitosan-based Cosmetics as Safe and Sustainable Products for Swimmers

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The widespread use of chlorine-based disinfectants in swimming pools, although effective for microbial control, is associated with the formation of various chlorination by-products (CBPs), many of which harm human health. Prolonged exposure to these compounds through inhalation and dermal absorption increases the detrimental effects on the skin, hair, and respiratory system of individuals such as swimmers and pool staff. Chitosan, a naturally derived biopolymer, has garnered considerable attention due to its biocompatibility, film-forming ability, and moisture retention characteristics. The reactive amino and hydroxyl groups of chitosan can also be easily modified to enhance its functionality for targeted applications. These features render chitosan a promising candidate for mitigating the harmful effects of CBPs. This review explores the potential role of chitosan in the formulation of personal care products designed to address the adverse effects of exposure to CBPs. The development of such functionalized, chitosan-based materials represents a sustainable and environmentally conscious approach to personal care. Further innovation in this field may facilitate the creation of advanced self-care products that support both the health and performance of swimming athletes, while contributing to the broader goal of green product development in the personal care industry.

1. Introduction

Swimming provides numerous health benefits, including improved cardiovascular function, muscular strength, and psychological well-being, but also poses risks due to chlorine-based disinfectants used to maintain pool hygiene. The pH of pool water in the range of 7.2-7.8 (Couto et al., 2021) allows the dissociation of hypochlorous acid (HClO) into hypochlorite ions (ClO^-) as free chlorine (Andrés et al., 2022). While effective in microbial control, the chlorine exerts strong oxidative activity that can disrupt disulfide and peptide bonds in keratin, compromising the structural integrity of hair, and contributing to hair discoloration through melanin degradation or damage to melanosomes in the hair cortex. Additionally, dermal absorption of hypochlorous acid and hypochlorite leads to the depletion of the natural oils or sebum in skin, resulting in dryness, irritation, and increased sensitivity (Paciência et al., 2021). Recent studies have reported that free chlorine can cause an imbalance between semaphorin-3A and nerve growth factors within the epidermis, leading to hypersensitivity, chronic irritation, and itchiness (Maeda et al., 2024). Moreover, chlorine readily reacts with organic matter from swimmers (urine, sweat, skin particles, and personal care products) to produce harmful CBPs like chloramine, trihalomethanes, haloacetic acids, and haloacetonitriles, which may cause respiratory issues such as respiratory tract irritation, irritant-induced asthma, bronchial hyperreactivity (Saleem et al., 2023), and airway inflammation (Peng et al., 2023).

To mitigate the harmful effects of chlorine exposure, a range of personal care products has been developed. Conventional formulations often include agents such as sodium thiosulfate and sodium ascorbyl phosphate, which chemically neutralize reactive chlorine species. Others incorporate moisturizing and protective ingredients like urea and dimethicone, where urea offers hydrating, mild exfoliating effects, while a silicon-based dimethicone forms an emollient layer that limits transepidermal water loss. However, growing environmental and health concerns surrounding synthetic additives have driven consumers' demand toward nature-derived, sustainable alternatives in cosmetic and personal care products. In this context, chitosan emerges as a versatile

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material with multiple beneficial properties for applications in cosmetics and personal care (Casadidio et al., 2019). Although native chitosan exhibits limited reactivity toward free chlorine, its molecular structure, which is rich in modifiable hydroxyl and amino groups, allows for targeted functionalization that enhances its protective efficacy. Despite its promise, there is no currently available literature which include critical evaluation of modified chitosan as a potential chlorine neutralizing agent. No systematic studies have compared different modification methods or tested these derivatives under practical conditions, and formulation constraints tailored to real-world swimming environment remain underdeveloped. Moreover, stability and performance testing of such formulations under the influence of varying pH levels and fluctuating organic loads, as well as their comprehensive safety profiles are still largely unexplored.

This review explores the potential of chitosan-based materials in addressing the health risks posed by chlorine and CBP exposure in swimming environments (Figure.1). It highlights recent advancements in the modification of chitosan and beneficial effects relevant to cosmetics formulation tailored for swimmers. The prospects of integrating chitosan in the development of environmentally sustainable cosmetic and personal care products are also discussed.

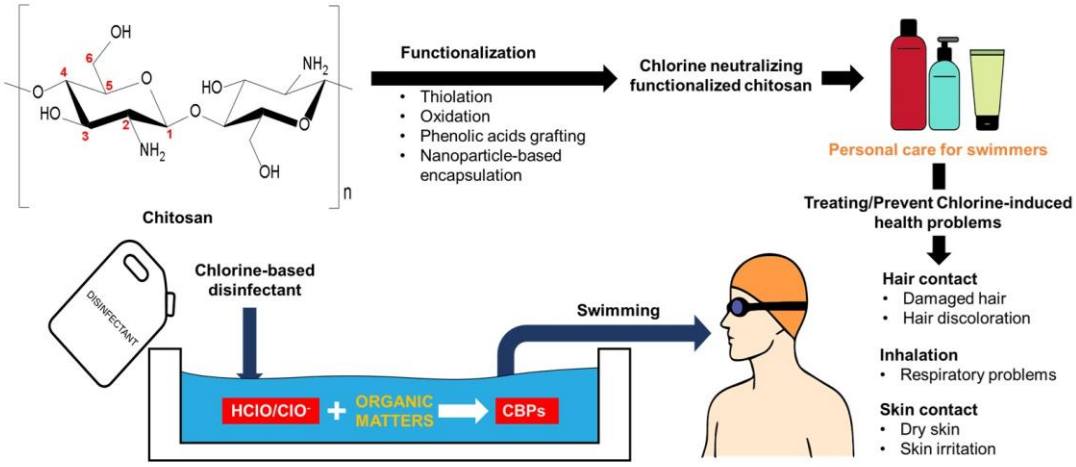

Figure.1: Modifications of chitosan for tailor-made personal care addressing the health risks posed by chlorine and CBPs

2. Extraction and characteristics of chitosan

Around 8 million tons of crustacean shell waste are discarded annually, mostly ending up in landfills or being dumped into the sea (Topić Popović et al., 2023). These shells contain 10-15 % chitin (Gîjiu et al., 2022), which can be converted into chitosan through deacetylation. This process is typically achieved through chemical treatment using concentrated alkali solutions, or biological treatment with proteinase or bacterial cultures under controlled temperature and time, resulting in free amino groups within the polymer chain. The degree of deacetylation, represented by the percentage of the amino groups in the polymer chain, strongly affects chitosan's properties. Additionally, hydroxyl groups of chitosan allow further modifications, making it adaptable for various applications (Ardean et al., 2021). The diverse applications of chitosan stem from its multiple beneficial characteristics, including antimicrobial, antioxidant activities, mucoadhesive property, penetration enhancing capability, film forming ability, and hydrophilicity that helps retain water for effective hydration. Another advantage of chitosan, which makes it an exceptionally versatile material, is the ease of functionalization, enabling modifications that alter its properties to suit specific needs. Thus, making chitosan a versatile biopolymer with diverse functional properties, rendering it particularly useful in the cosmetic industry, where it has been widely utilized with different functions in cosmetic formulations, such as emollient, antibacterial, antioxidant agent, and binding agent (Kulka and Sionkowska, 2023).

3. Chitosan functionalization for applications in swimmer-oriented products

3.1 Thiolation

Given the high reactivity of free chlorine with reduced sulfur moieties (Ra et al., 2025), the introduction of thiol groups represents a viable strategy for the chitosan functionalization. Thiolated chitosan, which has been extensively investigated for its strong adsorption capacity toward metal ions (Song et al., 2018) and organic dyes (Fernanda and Borsagli, 2019), demonstrates promising potential for the CBPs adsorption. This

modification aligns well with the growing interest in developing multifunctional and eco-friendly cosmetic ingredients that address both environmental and health concerns associated with swimming pool disinfectants. Thiolation of the chitosan backbone can generally be achieved via three principal approaches, depending on whether the hydroxyl, amino, or both functional groups are targeted (Alkabli, 2022). Thiol groups may be introduced either through direct substitution or by conjugation with thiol-containing ligands (Federer et al., 2020). Among various thiolated chitosan derivatives, chitosan-cysteine and chitosan-glutathione conjugates exhibit properties that meet the specific requirements for swimmer-oriented personal care applications. The highly nucleophilic thiol (-SH) groups in cysteine and glutathione facilitate the neutralization of free chlorine while maintaining a high degree of biocompatibility, biodegradability, and low toxicity of the polymer matrix. In addition to chlorine scavenging, these derivatives also demonstrate attributes favorable for cosmetic formulations, including mucoadhesivity, enhanced transdermal delivery of active ingredients (Negm et al., 2020), antioxidant activity, and biodegradability (Pokhrel and Yadav, 2019). These characteristics are particularly advantageous in the formulation of swimmer-focused skin and hair care products, where long-lasting protection and active ingredient delivery are critical. Chitosan-cysteine conjugates have been explored as nasal delivery powders, illustrating the adaptability and safety of thiolated chitosans across different delivery systems, including mucosal and topical applications (Kiss et al., 2022). Chitosan-glutathione derivatives have been officially recognized by the European Commission Cosmetics Ingredients (CosIng) database under the INCI name 'Chitosan Glutathionamide' for their functions as film-forming, skin-conditioning, and skin-protecting agents, reinforcing their regulatory acceptance and market readiness for cosmetic use. Despite their potential, thiolated chitosan has yet to be commercialized in swimmer-specific personal care products, highlighting an untapped market opportunity.

3.2 Selective C6-oxidation

Selective oxidation of hydroxyl groups at the C6 position of chitosan via using (2,2,6,6-tetramethylpiperidin-1-yl)oxidanyl (TEMPO) has been reported to yield water-soluble oxo-chitosan derivatives (Brasselet et al., 2019). In the presence of the TEMPO/NaOCl/NaBr system, the hydroxyl groups of chitosan are functionalized into nucleophilic aldehydes, which can be chlorinated via successive substitution of the hydrogen by chlorine on the α-carbon. However, under conditions with pH values above 5, such as those commonly found in swimming pool water, the haloform reaction can occur, which results in the formation of undesirable CBPs such as carboxylic acids and chloroform. Owing to this limitation, alternative functionalization strategies are preferable to ensure the safe and effective removal of free chlorine.

3.3 Phenolic acid grafting

Phenolic acids (PAs), a subclass of polyphenols, are naturally occurring aromatic compounds found in various fruits and vegetables. Known for their antioxidant, antimicrobial, and anti-inflammatory properties, PAs have garnered interest for applications in cosmetics and personal care products. Their electron-donating ability allows them to effectively neutralize free radicals and deplete free chlorine in aqueous environments (Kumar and Goel, 2019). This makes the incorporation of PAs into chitosan a promising approach in tackling the risks of free chlorine to swimmers' health. Recent studies have demonstrated the successful grafting of various PAs onto chitosan via copolymerization, resulting in materials with enhanced antioxidant and antimicrobial activities (Chen et al., 2022). In particular, gallic acid (GA) and caffeic acid (CA) have shown high efficacy in quenching free chlorine in chlorinated wash water, with concentrations as low as 10 μmol/L capable of reducing chlorine content by approximately 50 % (Toivonen and Lu, 2013). Although direct evidence regarding the chlorine-scavenging performance of chitosan-PA conjugates remains limited, both GA and CA-grafted chitosan have been extensively studied for safe use in food packaging, pharmaceuticals, and biomedical materials, demonstrating their biocompatibility. Therefore, PA-grafted chitosan presents a practicable method for enhancing the chlorine removal capacity of cosmetic formulations. Nonetheless, further research is necessary to investigate the applicability of PA-grafted chitosan in protecting swimmers from chlorine and CBPs in real-world conditions.

3.4 Nanoparticle-base encapsulation

Beyond chemical modifications, chitosan can also be engineered into nanoscale carriers for delivering active agents (Tran et al., 2023). Chitosan nanoparticles (CSNPs), which have been widely studied and optimized, offer a cost-effective and efficient platform for incorporating chlorine-neutralizing compounds without the need for complex chemical modifications. Compounds such as ascorbic acid, phenolic acids, and glutathione can be encapsulated within CSNPs, allowing for controlled release and prolonged effectiveness in cosmetic formulations. The nanoparticle-based delivery system promotes the dermal penetration of these active agents (Ta et al., 2021), thereby improving their bioavailability and protective efficacy against chlorine-induced damage, an important consideration in swimmer-targeted personal care products. Chitosan nanoparticles encapsulated

active agents for CBP removal represent a promising yet underexplored area, with most formulations are synthesized at laboratory scale, compelling further research until they can be commercialized.

4. Applications of chitosan and its derivatives in personal care for swimmers

To date, numerous cosmetics manufacturers have incorporated chitosan into their formulations, primarily employing chitosan as a film-forming and moisturizing agent. These attributes make chitosan a highly relevant ingredient for the development of swimmer-oriented personal care products. As outlined in the preceding sections, chemical functionalization of chitosan can further enhance its protective ability against free chlorine and CBPs, broadening its potential in advanced cosmetic applications. Practical chitosan-based formulations for swimmers should effectively neutralize chlorine in the 1-3 ppm range. They must remain stable within the typical pool water pH of 7.2 to 7.8 and maintain their effectiveness after prolonged exposure.

4.1 Applications in hair care

In regard to hair care formulations, particularly for swimmers, chitosan is a versatile ingredient that can be incorporated into pre-swim products to prevent chlorine absorption or included in shampoos to remove residual chlorine after swimming. Thanks to its cationic nature, chitosan readily binds to the negatively charged keratin on hair fibers, forming elastic films that not only strengthen the hair but also serve as a barrier preventing the permeation of chlorine into hair follicles (Guzmán et al., 2022). Moreover, functionalization of chitosan introduces active groups into the polymer film layer, which can be oxidized by free chlorine, thereby minimizing the damage to healthy hair. Furthermore, the chlorination of the hair follicles increases negatively charged cysteic acid groups, enhancing chitosan adsorption to the damaged hair shaft. This allows chitosan to restore the softness and strength of chlorine-exposed hair by forming a flexible film around the hair (Sionkowska et al., 2023). Its hydrating, antimicrobial, and antifungal properties also help soothe scalp irritation and prevent infections from pool water. These features make chitosan and its derivatives ideal for swimmer-specific hair care formulations like pre-swim hair sprays and post-swim shampoos and conditioners, especially when formulated with active agent-loaded chitosan nanoparticles for extended chlorine neutralization and CBP removal.

4.2 Applications in skin care

Chitosan and its derivatives are promising materials in swimmer-focused skin care products due to their diverse functionality. One of the key benefits of chitosan is its moisturizing effect, attributed to its water retention capacity, providing a hydrated layer that envelopes the skin surface, countering the dryness and irritation caused by exposure to chlorinated water. Additionally, the film-forming ability creates an elastic polymer barrier that not only reduces transepidermal water loss but also limits the absorption of chlorine into the skin (Morin-Crini et al., 2019). Thus, enhancing the elasticity and smoothness of the skin after exposure to chlorinated swimming pool water.

As previously mentioned, due to its cationic nature, chitosan can effectively bind to the negatively charged skin surface and enhance the permeation of active ingredients (Ma et al., 2022), such as bioactive molecules, through the skin. For instance, ascorbic acid can be encapsulated in chitosan nanoparticles to improve its stability, bioavailability, and chlorine-neutralization efficiency. Studies also suggested that chitosan exhibits absorption bands below 400 nm, which enable it to effectively block harmful UV radiation and minimize skin aging caused by exposure to UV radiation (Aranaz et al., 2018). This makes chitosan exceptionally useful for multifunctional sunscreen formulations that offer protection from UV-induced skin problems and photoaging.

Furthermore, native chitosan can be customized to fit the specific needs of swimmers via different functionalization methods. For example, phenolic acid-grafted chitosan enhances the antioxidant activity to combat oxidative stress, while thiolated chitosan derivatives excel in binding and neutralizing free chlorine. These versatile properties make both chitosan and its functionalized derivatives ideal for a wide range of cosmetics specifically designed for swimmers, including pre-swim lotions, sunscreens, and post-swim cleansers. For example, chitosan-based thiomers can be included in pre-swim lotion along with silicone or wax to yield a robust system, capable of forming a protective film with strong affinity for chlorine species, shielding the skin from exposure to CBPs.

4.3 Other applications

Apart from its application in skin and hair care, chitosan may be used topically in the nasal cavity, such as in nasal sprays, to protect against the inhalation of harmful aerosols containing chlorinated chemical species. This application is particularly important for frequent swimmers, who are constantly exposed to high chlorine concentration in swimming pools, where inhalation of chlorinated aerosols and CBPs like chloramines can irritate and trigger inflammation in the nasal mucosa. Moreover, formulations incorporating chitosan nanoparticles further enhance the residence time and absorption of active agents (Omidian et al., 2024). This

is due to the cationic nature of chitosan, which allows it to effectively bind to the mucins in the nasal passage and form protective films that prevent the penetration of chlorinated vapors. Thus, chitosan-based nasal spray products can provide a mucoadhesive barrier with anti-inflammatory effect, which protects the vulnerable mucins from chlorinated stimuli, potentially reducing upper respiratory symptoms among swimming athletes.

5. Future perspectives and challenges

As previously discussed, chitosan has been extensively studied and incorporated into various cosmetic formulations. With strategic functionalization, chitosan-based personal care products hold strong potential for addressing the specific needs of aquatic athletes. These formulations can be designed to provide multi-functional benefits, including chlorine neutralization, UV protection, and skin hydration, all of which are critical for maintaining healthy skin and hair under frequent aquatic exposure. Despite this potential, no studies have directly examined the interactions between chitosan–functionalized or otherwise, and aqueous chlorine or CBPs. As such, further research is essential to evaluate the viability of chitosan-based systems in swimmer-targeted cosmetics. Both *in vitro* and *in vivo* tests are needed to confirm chlorine neutralization effectiveness, evaluate cosmeceutical properties, and ensure safety for human use. Such studies would provide the scientific foundation needed for the regulatory approval and commercial adoption of chitosan-based swimmer-care products. An equally critical priority is the development of environmentally friendly, efficient, and scalable strategies for chitosan functionalization. Many current chemical modification techniques involve hazardous solvents or reagents that are unsuitable for personal care applications. Advances in green chemistry may enable more sustainable modification processes that align with the principles of clean beauty and the circular economy.

6. Conclusions

Chitosan, due to its versatile physicochemical and biological properties, has already been applied in the cosmetic industry as a multifunctional ingredient. However, its utilization in swimmer-targeted products remains limited owing to its insufficient intrinsic capacity to neutralize free chlorine. Strategic functionalization of hydroxyl or amino groups on chitosan has shown promise in addressing this limitation, positioning functionalized chitosan as a viable candidate for chlorine-protective cosmetic formulations. Functionalization approaches such as thiolation, oxidation, phenolic acid grafting, and nanoparticle-based encapsulation not only improve chitosan's native attributes but also enhance its chlorine-quenching capacity. These advanced derivatives offer strong potential as active compounds in a wide range of swimmer-specific personal care products, including hair and skincare formulations aimed at mitigating the harmful effects of chlorinated water. The incorporation of functionalized chitosan in nasal sprays presents an innovative avenue for protecting the respiratory tract from chlorinated aerosol inhalation, a common concern among swimming athletes. Despite these encouraging developments, further comprehensive research is essential to validate the efficacy, safety, and stability of these chitosan derivatives in real-world personal care applications. Rigorous *in vitro* and *in vivo* studies, along with scalable and eco-friendly production methods, will be crucial to advancing their integration into swimmer-oriented cosmetic solutions.

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