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VALORISATION OF BIOWASTE OF SNAIL SHELL AND WATER HYACINTH INTO FUNCTIONAL BIOPOLYMERS AND BIOPLASTICS: A REVIEW

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ABSTRACT

The growing accumulation of biowaste in the environment, coupled with rising concerns about plastic pollution, has intensified interest in sustainable materials derived from renewable resources. Among such wastes, snail shell residues and water hyacinth biomass occupy a unique position as both environmental liabilities and valuable feedstocks for biopolymer production. This review synthesizes current literature on (i) contamination of snail shells and water hyacinth by heavy metals and persistent organic pollutants (POPs), (ii) extraction and characterisation of chitosan from snail shells and carboxymethyl cellulose (CMC) from water hyacinth, (iii) microbial load considerations affecting material safety and performance, and (iv) development of biodegradable bioplastics based on chitosan–CMC systems reinforced with oil-palm fibre. Emphasis is placed on understanding contaminant binding mechanisms, process optimisation strategies, physicochemical and functional properties of the derived polymers, and their suitability for high-value applications. Key challenges related to contamination risks, microbial safety, scalability, and market competitiveness of bioplastics are critically discussed. The review highlights research gaps and future directions required to enable safe, standardised, and economically viable valorisation pathways for these abundant bioresources within a circular bioeconomy framework.

Keywords: Snail shell waste; Water hyacinth; Chitosan; Carboxymethyl cellulose; Bioplastics; Heavy metals; Circular bioeconomy.

INTRODUCTION

Escalating environmental pollution arising from synthetic plastics and poorly managed biological wastes has intensified global efforts toward the development of sustainable materials (Traverso et al., 2022; Rosenboom et al., 2022). Biopolymers derived from renewable resources and bio-wastes offer a promising pathway to reduce dependence on fossil-based plastics while simultaneously addressing waste disposal challenges (Pellis et al., 2022; Nwaka et al., 2025). Snail shell waste and water hyacinth biomass are generated in large quantities across tropical and subtropical regions, where they often accumulate as environmental nuisances due to inadequate management systems (Singh et al., 2021; Ajayi & Oyewole, 2023). Despite this, their biochemical composition renders them attractive feedstocks for the production of value-added biopolymers such as chitosan and carboxymethyl cellulose (CMC) (Chaiwarit et al., 2022; Amitaye & Uzah, 2025).

Beyond their material potential, these biowastes frequently function as sinks for heavy metals and persistent organic pollutants (POPs), raising concerns regarding their safe reuse (Baroudi et al., 2020; Al-Alam et al., 2024). A comprehensive understanding of contaminant accumulation, extraction technologies, microbial safety, and material performance is therefore essential for responsible valorisation (Monroy-Licht et al., 2024). This review synthesises existing knowledge across these themes and evaluates the feasibility of converting contaminated biowaste into safe, high-performance bioplastics reinforced with natural fibres.

Heavy Metals and Persistent Organic Pollutants in Biowaste

Contamination Pathways and Environmental Significance

Anthropogenic activities such as industrial discharge, intensive agriculture, mining, and urbanisation have contributed to the widespread distribution of heavy metals and POPs in terrestrial and aquatic ecosystems (Joseph et al., 2021; Vukašinović-Pešić et al., 2020). Due to their non-biodegradable and bioaccumulative nature, these contaminants persist in soils, sediments, and living organisms, posing long-term ecological and human health risks, including carcinogenicity, neurotoxicity, and endocrine disruption (Auma, 2014; Al-Alam et al., 2024).

Snail Shells as Environmental Indicators

Terrestrial snails are widely recognised as effective bioindicators because of their sedentary lifestyle, close contact with soil matrices, and ability to accumulate contaminants over time (Baroudi et al., 2020). Their shells, composed mainly of calcium carbonate with embedded organic matrices, can incorporate metals through substitution, adsorption, and lattice binding mechanisms (Ajayi & Oyewole, 2023). Consequently, discarded snail shells may function as long-term reservoirs of accumulated pollutants, particularly in contaminated environments (Nwagu, 2022).

Water Hyacinth as a Pollutant Sink

Water hyacinth (*Eichhornia crassipes*) is an invasive aquatic macrophyte with exceptional capacity for pollutant uptake. Its extensive fibrous root system and rapid biomass accumulation enable efficient sequestration of heavy metals and POPs from contaminated water bodies (Singh et al., 2021; Wang et al., 2024). While this property underpins its use in phytoremediation, the contaminated biomass generated poses significant secondary pollution risks if not properly managed (Tumembouw et al., 2024; Monroy-Licht et al., 2024).

Implications for Waste Valorisation

The presence of heavy metals and POPs in snail shells and water hyacinth complicates their reuse in food, pharmaceutical, cosmetic, or material applications (Ayoola et al., 2023; Ajayi, 2023). Without adequate screening and treatment, contaminants may be transferred into derived products or reintroduced into the environment, underscoring the need for robust contaminant assessment and safety evaluation prior to valorisation (Al-Alam et al., 2024).

Extraction and Characterisation of Biopolymers

Chitosan from Snail Shells

Chitosan is produced through partial deacetylation of chitin, a structural polysaccharide present in the organic matrix of snail shells (Pellis et al., 2022). Conventional extraction involves sequential deproteinisation, demineralisation, and alkaline deacetylation processes (Adekanmi et al., 2022). Several studies have demonstrated that snail-shell-derived chitosan can achieve degrees of deacetylation, molecular weights, and functional properties comparable to those of commercial crustacean chitosan, although the high calcium carbonate content necessitates efficient demineralisation (Bello et al., 2021; Tertsegha et al., 2024).

Emerging green extraction approaches, including natural deep eutectic solvents and ionic liquids, have shown potential for reducing chemical consumption and environmental impact, but further optimisation is required to ensure effective microbial control and scalability (Pellis et al., 2022; Rahman et al., 2023).

Carboxymethyl Cellulose from Water Hyacinth

Water hyacinth biomass is rich in lignocellulosic components, particularly cellulose, which can be isolated following appropriate pretreatment and purification (Chaiwarit et al., 2022; Febriyanti et al., 2024). The extracted cellulose can be converted into CMC via alkali-catalysed carboxymethylation, with reaction conditions strongly influencing degree of substitution, solubility, and rheological behaviour (Rasid et al., 2021; Ubaidillah et al., 2025). Water-hyacinth-derived CMC has been reported to perform comparably to conventional CMC in thickening, stabilising, and film-forming applications (Liu et al., 2024).

Physicochemical and Functional Characterisation

Analytical techniques such as Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), and thermal analysis are routinely used to confirm polymer synthesis and evaluate crystallinity, morphology, and thermal stability (Tertsegha et al., 2024; Jadhav et al., 2025). Functional assessments indicate strong metal-binding capacity for chitosan and favourable rheological behaviour for CMC, supporting their application in environmental remediation, packaging, and biomedical fields (Amitaye & Uzah, 2025; Liu et al., 2024).

Microbial Load and Material Safety

Sources of Microbial Contamination

Due to prolonged exposure to soil, freshwater, sediments, and organic wastes, snail shells and water hyacinth (*Eichhornia crassipes*) naturally harbour diverse microbial communities, including bacteria, fungi, and aquatic microorganisms. Commonly reported bacteria include *Bacillus*, *Pseudomonas*, *Escherichia coli*, *Enterococcus*, *Aeromonas*, and *Vibrio* species, while fungal genera such as *Aspergillus*, *Penicillium*, *Fusarium*, *Rhizopus*, and *Candida* are frequently isolated. In aquatic environments, water hyacinth additionally supports algae and cyanobacteria such as *Microcystis*, *Anabaena*, and *Oscillatoria* (Hassan et al., 2022; Nwosu et al., 2024; Pereira et al., 2023). Although harsh chemical treatments reduce microbial load during extraction, incomplete sterilisation, post-processing handling, and improper storage can result in recontamination (Pereira et al., 2023).

Impact on Applications

Elevated microbial loads compromise the safety and shelf life of biopolymers, particularly for food, pharmaceutical, and biomedical applications (Chen et al., 2021). Chitosan exhibits intrinsic antimicrobial activity due to its cationic nature, whereas CMC is more susceptible to microbial colonisation, necessitating stricter microbial control measures (Pereira et al., 2023; Liu et al., 2024).

Mitigation Strategies

Effective sterilisation techniques, controlled drying, moisture management, and appropriate packaging are essential to meet regulatory microbial limits and preserve material performance during storage and application (Hassan et al., 2022; Chen et al., 2021).

Bioplastics from Chitosan–CMC Systems Reinforced with Oil-Palm Fibre

Rationale for Composite Bioplastics

Pure biopolymer films often exhibit brittleness and high moisture sensitivity, limiting their practical applications (Brudzyńska et al., 2025). Blending chitosan and CMC exploits electrostatic interactions between cationic and anionic polymers, while reinforcement with oil-palm fibre enhances mechanical strength and stiffness (Hu et al., 2016; Asyraf et al., 2022).

Processing Techniques

Solution casting remains the dominant laboratory-scale method for producing chitosan–CMC–fibre films, whereas melt processing and extrusion offer pathways toward industrial scalability (Rahmi et al., 2017; Saepoo et al., 2023). Fibre dispersion, plasticiser concentration, and moisture control critically influence the final properties of the composites (Tan et al., 2022).

Performance Characteristics

Optimised composites demonstrate improved tensile strength, reduced solubility, and enhanced barrier properties compared with neat polymers (Kaewprachu et al., 2022). The inherent antimicrobial activity of chitosan further enhances the suitability of these materials for food-packaging and biomedical applications (Ponce et al., 2025).

Market Status and Challenges of Bioplastics

Despite increasing demand, bioplastics account for a relatively small proportion of global plastic production due to higher costs and limited policy support (Rosenboom et al., 2022; Shah & Gangadeen, 2023). While materials such as polylactic acid dominate the market, niche biopolymers derived from waste resources face challenges related to scalability, standardisation, and competitiveness with petroplastics (Moshood et al., 2021; Traverso et al., 2022).

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