

Review Article

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Green Synthesis of Nanoparticles Using Red Algae and Its Application in Dye Degradation – A Review

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ABSTRACT

Phyconanotechnology, the biosynthesis of nanomaterials using algal biomass and biomolecules, offers a renewable, cost-effective and environmentally benign alternative to physical and chemical fabrication routes. Red algae (Rhodophyta) are rich in natural reducing and stabilizing agents such as polysaccharides, phycobiliproteins, phenolics and pigments that support the synthesis of nanoparticles that additionally show therapeutic value, remarkably reactive oxygenspecies neutralizing and oxidativestress reducing activity. This review focuses the concept of marine algae-derived nanoparticles, particularly surveys on metal nanoparticles synthesized from red algae, including silver, gold, zinc oxide, iron oxide, titanium dioxide and copper oxide nanoparticles. The advantages and limitations of physical and chemical characterization techniques are compared and also outlined the pharmacokinetics of marine algae-derived nanoparticles. This review also highlights the applications of algae-derived nanoparticles in dye degradation.

Introduction

Algae are recognized for their capacity to hyperaccumulate and biotransform heavy-metal ions into more tractable forms, which makes them attractive biological templates for nanoparticle fabrication (Dhillon *et al.*, 2012). Phyconanotechnology refers to the application of algal biomass and biomolecules in the controlled synthesis of nanomaterials, that offers a sustainable alternative to conventional nanoparticle fabrication methods. A wide variety of processes have been developed for the synthesis of metal nanoparticles, but these methods are expensive and requires the use of

toxic and aggressive chemicals as reducing and capping agents (Vasquez *et al.*, 2016). Marine algae serve as a renewable and ecofriendly reducing and capping agent which minimizes the usage of harsh chemicals. The bioactive compounds derived from marine algae further enhance the functional properties of the synthesized nanoparticles, expanding their potential applications in medicine, agriculture, and environmental remediation (Chan *et al.*, 2022). Red algae are especially promising in this respect because they are rich in sulfated polysaccharides, phycobiliproteins, phenolic compounds and pigments that can reduce and cap metal ions. This review aims to summarize the current knowledge on the

biosynthesis and characterization of metal nanoparticles using red algae (Rhodophyta) and to evaluate their pharmacokinetic property and also surveys the reported biological and environmental applications.

Green Synthesis of Nanoparticles Using Red Algae

Marine Algae-Derived Nanoparticles (MADNs), synthesized using naturally occurring algal biomolecules, offer advantages over conventional delivery systems, including improved solubility of hydrophobic drugs, enhanced physiological stability and the possibility of controlled or targeted release (Menaar *et al.*, 2021). Red algae, rich in natural reducing and stabilizing agents, support environmentally friendly nanoparticle synthesis that additionally confers therapeutic value, particularly ROS-neutralizing and oxidative-stress-reducing activity relevant to cancer, cardiovascular disease and neurodegeneration (Aziz *et al.*, 2020). In addition to therapeutics, it also exhibits considerable potential in diagnostic imaging, including magnetic resonance imaging (MRI) and fluorescence imaging, through the incorporation of targeted ligand conjugates (Anvar *et al.*, 2023; Ahmed *et al.*, 2025). Furthermore, their inherent biocompatibility and biodegradability may mitigate cytotoxicity concerns, supporting their application in antimicrobial coatings, wound healing and tissue regeneration (Hou and Allakhverdiev, 2023; Yedoti and Supraja, 2024).

Metal Nanoparticles Synthesized from Red Algae and its Biological Properties

Silver Nanoparticles

Silver nanoparticles have received attention because of their unique chemical and physical properties, which differ greatly from those of bulk materials as well as their potential for technological applications. Silver nanoparticles exhibit tremendous application in drug delivery, wound healing, sensor applications, textile industry, cosmetics and also used as antimicrobial agent. Ibraheem *et al.*, (2016) synthesized silver nanoparticles (AgNPs) by reducing silver nitrate with an alcoholic extract of *Acanthophoraspicifera*; NP formation was confirmed by a dark-brown colour change and XRD, which showed cubic crystalline particles of 33–81 nm, with FTIR confirming capping functional groups. The AgNPs significantly inhibited both Gram-positive (*Staphylococcus aureus*, *Bacillus subtilis*) and Gram-

negative (*Salmonella* spp., *Escherichia coli*) bacteria as well as *Candida albicans*. Using *Spyridiafusiformis*, AgNPs were synthesized and characterized by UV-Vis spectroscopy, FTIR, TEM and XRD. These nanoparticles showed strong antibacterial activity, with maximum inhibition zones of 26 mm and 24mm against *Klebsiella pneumoniae* and *S. aureus* respectively at 100 µg/mL Murugesan *et al.*, (2017).

A polysaccharide extracted from *Gracilariabirdiae* was used as both reducing and stabilizing agent for AgNP synthesis across varying polysaccharide concentrations (0.02–0.05% v/v) and pH (10–11). UV-Vis confirmed a characteristic plasmon peak at 410 nm, with DLS/TEM indicating hydrodynamic diameters of 20.2–94.9 nm and stable, negatively charged, spherical particles that remained non-agglomerated over four months, showing antimicrobial activity against *E. coli* (de Aragão *et al.*, 2019). Green AgNPs synthesized from aqueous extracts of *Halymeniaporphyriiformis* and *Solieria robusta*, compared and tested against four oral pathogens such as *Staphylococcus aureus*, *Streptococcus viridans*, *Lactobacillus acidophilus*, *Lactobacillus brevis*. XRD indicated a smaller particle size for *H. porphyriiformis* than *S. robusta* AgNPs. Both showed moderate antibacterial activity against all strains except *L. acidophilus*, against which maximal inhibition occurred at lower concentrations, although *H. porphyriiformis* AgNPs more effective owing to their smaller size (Khan *et al.*, 2022).

Zinc Oxide and Iron Oxide Nanoparticles

Zinc oxide and iron oxide nanoparticles are versatile biomaterials used in nanomedicine for antimicrobial activity, cancer treatment and magnetic resonance imaging (Unsal *et al.*, 2026). Through green synthesis, their combined nanocomposites merge magnetic and optical properties to provide enhanced biocompatibility and multi-functional performance for biomedical applications (Sher *et al.*, 2024). Iron oxide nanoparticles (Hv-Fe₃O₄-NPs) from *Hypneavalentiae* were produced for cancer-therapy applications, confirmed via UV-Vis, FTIR, SEM, TEM, EDS, XRD, DLS and VSM. The nanoparticles showed notable DPPH and hydrogen-peroxide-scavenging (antioxidant) activity and effective anticancer action against MDA-MB-231 breast cancer cells (IC₅₀ = 33.89 µg/mL) relative to A549 lung cancer cells (IC₅₀ = 66.79 µg/mL), inducing ROS-mediated apoptosis. RT-PCR confirmed downregulation of AKT/PI3K and upregulation of PTEN at 34 µg/mL, with

molecular docking supporting favourable binding of algal compounds to AKT/PI3K pathway proteins. Iron oxide nanoparticles synthesized from *Portieriahornemannii* extract were similarly confirmed via UV-Vis, FTIR, XRD, SEM, TEM and SAED, and demonstrated strong antibacterial efficacy against both Gram-positive and Gram-negative bacterial strains (Baskar *et al.*, 2024).

Gold Nanoparticles

Gold nanoparticles (AuNPs) have been attracting enormous attention on account of their outstanding physico-chemical properties, which make them suitable for application in many fields such as the pharmaceutical and food industry (Nejati *et al.*, 2022). AuNPs are of particular interest in the field of nanomedicine, since the study of their properties has revealed that they could be valuable tools for the diagnosis and treatment of cancer (D' Acunto *et al.*, 2021). Moreover, their antimicrobial, antiviral and antioxidant capacity has also been investigated (Okkeh, *et al.*, 2021). *Champia parvula*-mediated gold nanoparticles (Cp-AuNPs) exhibited an SPR peak at 550 nm, spherical morphology with an average size of 20 nm, and a crystalline structure, as confirmed by UV-Vis, TEM/SEM, and XRD analyses, respectively.

FTIR analysis identified algal-derived organic compounds involved in nanoparticle capping and stabilization. The nanoparticles demonstrated strong antioxidant and free-radical-scavenging activity and marked anticancer potential against A549 lung cancer cells Viswanathan *et al.*, (2023).

AuNPs synthesized using green (*Ulva rigida*), brown (*Cystoseiramyrica*) and red (*Gracilariaboliifera*) algal extracts were compared, obtaining particle sizes of 9, 11 and 13 nm respectively. Red algae-capped AuNPs showed intermediate cytotoxicity toward Hfb-4 skin cells (IC₅₀ 64 µg/mL, versus 102 µg/mL for brown and 32 µg/mL for green algae-derived particles), while *G. foliifera*-derived AuNPs achieved the highest anticancer activity against MCF-7 cells (92.13% at 188 µg/mL, IC₅₀ 30 µg/mL). Green algae-derived AuNPs showed superior antimicrobial activity overall, and the fungal species *T. cataneum* and *T. mentagrophytes* were particularly susceptible to AuNPs from all three algal sources, supporting their potential as alternative anticancer and antimicrobial agents (Algotiml *et al.*, 2022).

A related core-shell nanobiocomposite, synthesized using R-phycocyanin extracted from *Porphyridium purpureum* to coat a bimetallic silver-zinc oxide (Ag-ZnO) core, yielded particles averaging 33 nm and showed dose-dependent cytotoxicity against MCF-7 cells, with maximum cytotoxicity of 59% and an IC₅₀ of 100 µg/mL, indicating potential relevance for cancer therapeutics (Nunes *et al.*, 2025).

Titanium Dioxide and Copper Oxide Nanoparticles

Titanium oxide (TiO₂) has excellent photocatalytic performance and chemical stability; conversely, it is low cost and biologically safe. For these reasons, TiO₂ has received special attention for its purification applications and as an antimicrobial agent (Shaban, *et al.*, 2019). TiO₂ nanoparticles from two red algae (*Bostrychia tenella*, *Laurencia obtusa*), a green alga (*Halimeda tuna*), a brown alga (*Sargassum filipendula*) and a marine sponge (*Carteriospongiafoliascens*), synthesized and characterized by XRD, SEM, UV-Vis, EDS, XPS and FTIR. Incorporated into antifouling marine-paint formulations and tested over 108 days on immersed steel panels in Alexandria's Eastern Harbour, the *B. tenella*- and *C. foliascens*-based coatings outperformed a commercial antifouling paint, with heavy barnacle fouling observed only on the commercial control and no adverse effects on surrounding seawater chemistry (Alarif *et al.*, 2023). The ecological and economic burden of *Ulva lactuca* and *Gracilaria verrucosa* overgrowth affecting Manila clam (*Ruditapesphilippinarum*) cultivation on Italy's Adriatic coast. Marmioli *et al.*, (2024) synthesized CuO nanoparticles from both algal species, characterized by FTIR, XRD, HRTEM/EDX and zeta potential. Nanoparticles synthesized from both species exhibited comparable physicochemical characteristics and antimicrobial activity, due to the presence of similar algal metabolites, highlighting the potential of these problematic macroalgae as valuable resources for sustainable nanomaterial production.

Mechanism of Algae-Mediated Nanoparticle Biosynthesis

The diverse biochemical composition of algae makes them promising biological resources for the green synthesis of metallic nanoparticles. Biosynthesis begins when a metal precursor solution is incubated with algal extract; algal biomolecules, including antioxidants,

pigments, phycobilins, chlorophylls, oils, minerals, carbohydrates, proteins, PUFAs and other phytochemicals, reduce metal ions to their zero-valent state. The bioreduction process generally occurs in three successive phases: activation, growth, and termination. During the activation phase, metal ions are enzymatically reduced, initiating nucleation and often producing a characteristic change in colour. The growth phase involves the aggregation of the newly formed nuclei into thermodynamically stable nanoparticles with varying sizes and shapes. Finally, during the termination phase, further growth and aggregation cease, resulting in the development of the final nanoparticle morphology. Factors such as temperature, pH, incubation time, substrate concentration, static condition and agitation govern the resulting physical characteristics of nanoparticles (Prasad *et al.*, 2016).

The biological activity of marine-derived nanoparticles is closely tied to their unique physicochemical attributes such as high surface-area-to-volume ratio, nanoscale dimensions and tunable surface functionalization, which support receptor-specific targeting and improved drug-delivery precision, reducing off-target toxicity (de Almeida *et al.*, 2025). Many marine nanoparticles also modulate oxidative stress by neutralizing reactive oxygen species and protecting cellular DNA, lipids and proteins from oxidative damage, relevant to neurodegenerative and cancer pathologies, and can further influence intracellular signaling pathways governing apoptosis, autophagy and inflammation (Imran *et al.*, 2021; Summer *et al.*, 2024). Antimicrobial activity is commonly mediated through microbial membrane disruption and enzymatic interference, offering a potential route against antibiotic-resistant pathogens, while inherent biocompatibility and biodegradability reduce immune activation and improve in vivo retention and efficacy (Vasyukova *et al.*, 2021).

Characterization Techniques for Synthesized Nanoparticles

Physical, chemical and biological characterization together confirm nanoparticle formation and assess functional suitability. Physical characterization evaluates the absorption, particle size, morphology and size distribution using techniques such as UV-Vis spectroscopy, SEM, TEM and DLS, respectively (Rengasamy *et al.*, 2020). Chemical characterization determines the elemental composition, crystalline structure, surface functional groups and surface charge

through techniques including FTIR, XRD and zeta-potential analysis. Biological characterization further assesses functional performance, particularly antioxidant activity using DPPH and ABTS assays and cytotoxicity through MTT and cell-viability assays (Faisal *et al.*, 2023; Ahmad *et al.*, 2022; Shah *et al.*, 2020).

Physical Characterization

UV-Visible spectroscopy measures light extinction across the ultraviolet (185–400 nm) and visible (400–700 nm) ranges, providing rapid, low-cost insight into nanoparticle size, shape and concentration. It is a fast, simple and sensitive technique, which employs minimal sample preparation and serves as a standard first-pass characterization tool for nanoparticles. UV-Vis spectroscopy provides both quantitative and qualitative information about the investigated material (Ghosh *et al.*, 2024).

Scanning Electron Microscopy (SEM) resolves the surface topography, morphology and, when paired with an energy-dispersive X-ray detector, elemental composition of a nanomaterial, though it gives no insight into internal structure. An electron beam generated at 1–30 kV is focused into a fine probe that rasters across a conductive, vacuum-mounted sample, and electrons scattered from the surface are captured to build an image, typically achieving resolution near 1 nm at magnifications up to roughly 300,000x (Akhtar *et al.*, 2018). The technique is widely used to confirm the morphology of algae-synthesized nanoparticles. Mansour *et al.*, (2022) employed SEM to confirm the porous morphology of zinc oxide nanoparticles green-synthesized using the red seaweed *Pterocladia capillacea*, which exhibited a high BET surface area of 113.75 m²/g, developed for dye-contaminated wastewater treatment. Alarif *et al.*, (2023) used SEM to compare crystallite morphology across titanium dioxide nanoparticles synthesized from several red, green and brown algae and a marine sponge for antifouling marine-paint formulations, finding the smallest and most effective crystallites in the *Bostrychia tenella*- and *Carteriospongia foliascens*-derived samples. The main advantages of SEM are its high resolution, pseudo-three-dimensional surface detail and real-time imaging capability. The key limitations include the requirement of electrically conductive or coated specimens, restricted sample-size compatibility, limited penetration depth, and high-vacuum operating conditions, which may alter the sample from its native state. (Aziz *et al.*, 2025).

Transmission Electron Microscopy (TEM) probes a material's internal structure, morphology, crystallinity and stress state at higher resolution and magnification than SEM. An electron beam accelerated at roughly 100 kV is focused through an ultra-thin specimen, and the transmitted electrons strike a fluorescent screen to form an image whose contrast reflects local sample density (Aziz *et al.*, 2025). Its high-resolution variant (HRTEM) is frequently used to resolve fine nanoparticle detail in seaweed-mediated synthesis. Murugesan *et al.*, (2017) employed TEM to confirm the formation of silver nanoparticles ranging from 5–50 nm using the red alga *Spyridia fusiformis*. Similarly, de Aragao *et al.*, (2019) used TEM and DLS to demonstrate that polysaccharide-capped silver nanoparticles synthesized from *Gracilariabirdiae*, with sizes ranging from 20.2–94.9 nm, remained stable and non-agglomerated for up to four months. Viswanathan *et al.*, (2023) utilized TEM to confirm spherical, 20 nm gold nanoparticles synthesized from *Champia parvula* with antioxidant and anticancer activity. The advantages include superior resolution and detailed morphological and elemental data, low operating voltage relative to SEM, and the ability to image biological specimens directly. Its major limitations include the extensive sample preparation required, as specimens must be sufficiently thin and may undergo alterations during fixation or embedding, along with susceptibility to electron-beam damage and considerably higher instrumentation and operational costs compared with SEM (Aziz *et al.*, 2025).

Dynamic light scattering (DLS) is a rapid and non-invasive technique for determining particle-size distribution in the nanometre to submicron range by measuring temporal fluctuations in scattered laser-light intensity arising from Brownian motion. The hydrodynamic particle size is calculated using the Stokes–Einstein relationship. DLS is particularly suitable for dilute, relatively monodisperse suspensions. However, its accuracy can be compromised in highly concentrated or polydisperse systems (Babick, 2020).

Chemical Characterization

Fourier-Transform Infrared spectroscopy (FTIR) measures absorption of mid-infrared radiation (4000–400 cm^{-1}) associated with changes in molecular dipole moment, identifying functional groups and bond characteristics relevant to capping-agent identity and nanoparticle–biomolecule interaction (Pasiczna-Patkowska *et al.*, 2025).

X-ray diffraction (XRD) is an important technique for characterizing nanoparticles, particularly for determining crystallinity, identifying crystalline phases, and estimating crystallite size. The diffraction peaks are compared with standard JCPDS/ICDD reference patterns to verify the expected phase and detect unreacted precursors or secondary phases. The broadening of diffraction peaks in nanomaterials, resulting from their small crystallite size, can be used to estimate the average crystallite size using the Scherrer equation, ($D = K\lambda/\beta\cos\theta$) (Patterson, 1939). Peak intensity and sharpness provide information on the degree of crystallinity, while peak shifts and asymmetric broadening may indicate lattice strain or structural defects. Since XRD does not provide direct information on particle morphology or surface chemistry, it is commonly used alongside TEM/SEM and FTIR, which provide complementary information on particle size, morphology, and surface functional groups, respectively (Mourdikoudis *et al.*, 2018).

Zeta potential is widely used as an indirect indicator of colloidal stability and surface charge in nanoparticle suspensions. Nanoparticles exhibiting zeta-potential values above +30 mV or below –30 mV are generally considered to have greater colloidal stability because electrostatic repulsion between similarly charged particles can reduce aggregation. Values within this range may indicate an increased tendency toward particle agglomeration. In green-synthesized nanoparticles, zeta potential can also provide indirect evidence of surface functionalization by algal or plant-derived biomolecules, particularly through the adsorption of charged functional groups such as carboxyl, hydroxyl, and other anionic moieties. Because zeta potential is influenced by factors such as pH, ionic strength, and dispersion conditions, these parameters should be reported alongside the measured values. Zeta-potential analysis is commonly complemented by DLS to obtain information on hydrodynamic size and polydispersity, thereby providing a more comprehensive assessment of nanoparticle stability and suitability for biological or catalytic applications (Bhattacharjee, 2016).

Pharmacokinetics of Marine Algae-Derived Nanoparticles

The in vivo pharmacokinetic behavior of MADNs, encompassing absorption, distribution, metabolism and excretion (ADME), is essential for evaluating their therapeutic viability.

Absorption depends on particle size, surface charge and hydrophilicity, with smaller, surface-modified particles generally showing improved uptake (Mohibbullah *et al.*, 2022). Organ-level biodistribution is shaped by nanoparticle physicochemical properties and the use of targeting ligands, which can improve delivery specificity while limiting off-target accumulation. Metabolic transformation, governed by the specific bioactive composition and surface chemistry of MADNs, influences their stability, activity and safety profile, while renal or hepatic excretion is strongly size- and shape-dependent, with smaller particles cleared more efficiently via renal filtration (Sharma *et al.*, 2023; Faisal *et al.*, 2022). Long-term monitoring of biodistribution and metabolism remains essential to rule out unwanted accumulation and confirm safety (Shrotriya *et al.*, 2025).

Preclinical studies documenting MADN efficacy in photoprotection, cancer therapy, wound healing, anti-inflammatory and antioxidant applications underscore the translational relevance of this pharmacokinetic profiling, while attention to individual genetic and physiological variability may further support personalized, lower-toxicity therapeutic design (Wang *et al.*, 2019; de Almeida *et al.*, 2025). These principles, although derived largely from studies on marine algal nanoparticles in general, are presumed to extend to red-algae-synthesized nanoparticles such as Ag, Au, ZnO, and Fe₃O₄ systems reported from genera such as *Gracilaria*, *Gelidiella*, and *Chondrus*, though dedicated ADME studies isolating red-algal nanoparticle behaviour in vivo are still lacking in the literature reviewed.

Complementary insight comes from pharmacokinetic work on individual red- and brown-algal bioactive compounds rather than nanoparticles themselves. Mohibbullah *et al.*, (2022) provide one of the more detailed pharmacokinetic pictures available for an algal-derived compound fucoxanthin, a brown-algal carotenoid structurally related to the phycobiliprotein and carotenoid pigments found in red algae. This study shows that it undergoes gastrointestinal hydrolysis to fucoxanthinol prior to intestinal absorption, and that nanoparticle-guided delivery increases its bioavailability, including brain bioavailability, relative to the free compound.

The parent fucoxanthin exhibited substantially more rapid elimination than its metabolites, demonstrating that nanoencapsulation can significantly influence the pharmacokinetic behavior and systemic disposition of algal-derived bioactive compounds.

Similarly, Harasym *et al.*, (2025) reported that the physicochemical instability and poor aqueous solubility of phlorotannins and other algal polyphenols can limit their oral bioavailability, posing an important challenge for their therapeutic application. The selection of an appropriate nanodelivery system can enhance the stability, bioavailability, and therapeutic potential of red-algal-derived bioactive compounds. In particular, red-algal bromophenols may interact with cellular targets through relatively specific and high-affinity mechanisms, whereas the structurally complex phlorotannins of brown algae can exhibit broader and more diverse interactions. These differences may influence the pharmacokinetic and pharmacodynamic behaviour of red-algal compounds following nanoformulation. However, experimental evidence on the pharmacokinetic performance of nanoformulated red-algal bioactives remains largely unexplored experimentally.

Marine-derived nanocarriers, including those formulated from algal polysaccharides such as red-algal carrageenan and agarose, have gained attention within the broader framework of nanoscale drug delivery and pharmacokinetic optimization. The incorporation of marine bioactive compounds into nanocarrier platforms, including polymeric nanoparticles, liposomes, micelles, hydrogels, and exosome-like vesicles, can enhance their physicochemical stability, bioavailability, controlled-release characteristics and targeting efficiency compared with free bioactive compounds. Collectively, the available literature suggests that the pharmacokinetic behaviour of marine algal-derived nanomaterials is influenced by its physicochemical properties, including particle size, surface charge, and surface chemistry. Although nanoencapsulation has consistently demonstrated potential for improving the bioavailability and targeted delivery of algal bioactives, (Gautam *et al.*, 2026).

Application of Red Algae Derived Nanoparticles in Dye Degradation

Textile azo dyes, including Congo red, malachite green, and methyl red, represent significant environmental and public health concerns due to their carcinogenic potential, chemical persistence, and resistance to natural degradation, underscoring the need for efficient and sustainable biodegradation approaches (Suhaimi *et al.*, 2022). Metal-oxide nanoparticles offer strong catalytic and adsorptive capacity for dye removal, generating reactive species under appropriate conditions (Rather and

Mandal, 2023). Dye degradation by metal-oxide nanoparticles proceeds mainly through photocatalysis, wherein light absorption generates electron-hole pairs that yield reactive hydroxyl radicals capable of breaking down dye molecules, complemented by adsorption-desorption at the nanoparticle surface and efficient electron-hole separation that sustains redox-driven dye breakdown (Hua *et al.*, 2020).

TiO₂ nanoparticles are especially valued for photocatalytic remediation, ZnO nanoparticles for combined photocatalytic, UV-protective, and antibacterial function, Fe₃O₄ nanoparticles for wastewater treatment, MRI, and targeted delivery, and CeO₂/CuO nanoparticles for catalytic and antibacterial application, with material choice guided by application-specific requirements (Saleh, 2019; Wang, 2007; Anushree *et al.*, 2021).

Silver nanoparticles (AgNPs) phycosynthesized from *Hypneamusciformis* were characterized by FT-IR and atomic force microscopy and demonstrated impressive photocatalytic degradation of methyl orange dye under visible-light illumination (Selvam and Sivakumar, 2015). Similarly, AgNPs synthesized from *Gracilariacorticata* extract, confirmed by a UV-Vis absorption peak at 380 nm and surface plasmon resonance, spherical morphology of approximately 100 nm by HR-SEM, and a positive zeta potential of 7.7 mV indicating moderate colloidal stability, exhibited strong photocatalytic activity against malachite green dye under visible light (Poornima and Valivittan, 2017). *Gracilaria edulis*-mediated Ag₂O nanoparticles have also been explored for the remediation of dye effluents, with reported implications for both soil and water quality (Visu *et al.*, 2026).

Metal oxide nanomaterials synthesized using red algae have demonstrated considerable potential for broad-spectrum photocatalytic degradation, coupled with enhanced reusability and operational stability. Manganese dioxide nanoparticles (α -MnO₂) green-synthesized using the edible freshwater red alga *Lemanea manipurensis*, with a UV-Vis absorption band centered at 368 nm and an optical band gap of 2.44 eV, effectively degraded rhodamine B, methyl orange and methylene blue dyes, with degradation rate constants of 0.06781, 0.04323 and 0.03831 min⁻¹ respectively. The photocatalyst retained its catalytic activity and structural stability over four consecutive reuse cycles, highlighting its potential for practical and sustainable wastewater treatment applications (Borah *et al.*, 2022).

In addition to photocatalytic degradation, red algae-derived nanoparticles have also demonstrated efficient dye removal through adsorption-based mechanisms. Zinc oxide nanoparticles synthesized from *Pterocladia capillacea* extract were evaluated for their capacity to adsorb Ismate Violet 2R (IV2R) dye. Characterization by UV-Vis, FTIR, SEM, XRD, and BET analysis with surface area 113.751 m²/g and average pore size of 2.527 nm confirmed nanoparticle formation and maximal dye removal (99%) occurred at 0.08 g ZnO-NPs, pH 6, 55°C and 120 minutes contact time, with an adsorption capacity of 72.24 mg/g. Adsorption followed the Freundlich isotherm and pseudo-second-order kinetics, and thermodynamic analysis indicated a spontaneous, endothermic process, supporting its application in dye-contaminated wastewater treatment (Mansour *et al.*, 2022). Collectively, these studies establish red algae as versatile and sustainable precursors for nanoparticles capable of remediating dye pollutants through both photocatalytic degradation and adsorption pathways.

Future Perspectives

Red algal extracts and biomolecules have been used successfully as reducing and capping agents for silver, gold, zinc oxide, iron oxide, titanium dioxide and copper oxide nanoparticles, yielding materials with antimicrobial, antioxidant, anticancer, antifouling and dye-adsorptive or photocatalytic properties. Marine algae-derived nanoparticles combine the advantages of high surface-area-to-volume ratio, tunable surface functionalization, biocompatibility and biodegradability, and a three-phase bioreduction mechanism controlled by temperature, pH, incubation time, substrate concentration and agitation governs their final size and shape.

The growing interest in marine algae-derived nanoparticles (MADNs) as therapeutic agents, comprehensive *in vivo* pharmacokinetic data specific to red algae-derived nanoparticles remain scarce, representing a significant translational gap. The reported pharmacokinetic datasets for algal-derived nanomaterials originate from brown-algal (Phaeophyceae) systems rather than red-algal ones.

Thus, systematic studies on *in vivo* pharmacokinetic investigations specifically focusing on red-algal-derived nanomaterials are therefore required to establish their ADME profiles and to facilitate their translation into practical biomedical applications.

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