Plant-based proteins: Key sources and production methods

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Abstract

The global protein crisis, which has been driven by the population explosion and environmental cost of traditional farming, requires novel and sustainable remedies. The chapter discusses how novel opportunities can be generated by the combination of two promising frontiers, like seaweed as an all-useful resource in the sea and green nanotechnology. The seaweed extracts that are abundant in bioactive compounds can be used as natural nanofactories in the production of metallic and metal oxide nanoparticles in an eco-friendly manner. The mechanisms of this synthesis are discussed and enlighten on how seaweed bioactive stabilize nanoparticles and reduce toxic substances. Synthesized nanoparticles are then characterized with regard to

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their special physicochemical properties. The core of the chapter is that nanoparticles synthesized from seaweeds are used in multifaceted ways to improve protein diet and production. Further the use of nanoparticles as nutrient delivery systems to enhance bioavailability, to support new protein-enriched foods, and in sustainable agriculture and aquaculture to increase yields and feed efficiency. Most importantly, the chapter draws attention to the most critical aspects of safety, toxicity, and the regulatory environment of nanoparticles in the food chain. The synergistic model synthesized seaweed nanoparticles have the potential to improve the whole energy chain of protein, and this chapter puts forward a possible, circular route of developing a more robust and secure global food system.

1. Introduction

Global food security has been very challenging in the twenty-first century, with the increased need to consume nutritious and sustainable protein. The rapid population expansion, the rise in income, urbanization, and increased ecological footprint of traditional agriculture have been united to introduce what could be referred to as a global protein crisis (Lumsden et al., 2024). In spite of the fact that the traditional production of livestock can be taken as one of the primary sources of proteins. Fig. 1 summarizes the integrated role of modern technologies in advancing sustainable protein solutions. This is a resource-intensive process that puts an

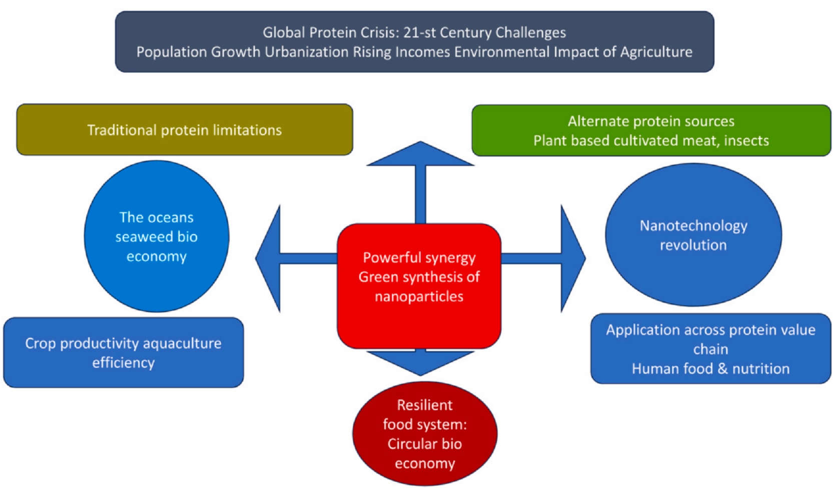

Fig. 1 Conceptual framework illustrating the role of green nanoparticle synthesis in addressing the global protein crisis.

irresistible pressure on land, freshwater sources, and causes greenhouse gas emissions to a considerable degree. This paradigm is being considered as unsustainable in its current form. It is not a crisis of quantity but a crisis of quality and equitable allocation, and this should radically change the current population's response to generate, and eat protein to feed the growing world (Niu et al., 2024).

In this response, both the scientific and industrial communities have switched attention to the frontier of alternative sources of proteins. Plant-based proteins, plant-grown meats, and insect farming are signs that our relationship to food will undergo a paradigm shift (Kaplan & McClements, 2025). However, the majority of these new sources have drawbacks on their own, including antinutritional status, inadequate sensory properties, and incomplete amino acid profiles. It is on this complex ground that the ocean, the majority of which is over seventy percent of our earth, is emerging as a core and unexploited source of solutions. Marine macroalgae, commonly referred to as seaweed, are a highly diverse and abundant marine resource that has long been able to support the coastal communities over the millennia (Rath et al., 2025). Being a photosynthetic organism, it proliferates fast, without the need for soil, fresh water, or fertilizer. Seaweeds captures carbon and prevents coastal eutrophication. It has a great biochemical diversity with unique polysaccharides and high-quality proteins, as well as essential minerals and powerful bioactive compounds, which make it much more than a foodstuff, but the basis of a new bio economy (Cotas et al., 2024).

In parallel with the discovery of new biological resources, there is another technological revolution that is being experienced at the molecular level. Nanotechnology, the manipulation of matter at 1–100 nm, has infiltrated a wide range of disciplines, including medicine and materials science, and now the implementation of nanotechnology in food and agriculture is bringing innovative opportunities (Khatoon & Velidandi, 2025). At such a small scale, materials have new optical, electrical, and catalytic properties. When applied to food, this means that there is a potential for better delivery systems of the nutrient, better food safety due to new packaging methods, and the creation of functional ingredients with better characteristics. However, the common synthesis of nanoparticles traditionally involves the usage of toxic substances and processes that consume a lot of energy (Fahim et al., 2024). This poses a question of their influence on the environment and biocompatibility, which places a significant obstacle in the safe use of nanoparticles in the food chain.

This chapter suggests a synergy of the certain overlapping challenges that exist between the green synthesis of nanoparticles with seaweed extracts. This is a safest and sophisticated way of bridging the sustainability of a marine resource with nanotechnological precision. Seaweed extracts, which are biologically complex mixtures of reducing and stabilizing biomolecules, can be used as natural nanofactories and thus permit the synthesis of metallic and metal oxide nanoparticles as well as composite nanoparticles to be innately biocompatible (Morgan & Aboshanab, 2024). Such nanoparticles produced by seaweeds can subsequently be utilized to improve all the nodes in the protein value chain, including increasing the productivity of protein crops with the help of nano-biofertilizers and the health and feed efficiency of aquaculture (Khan et al., 2024). This technology will be helpful in improving the nutritional bioavailability and functional properties of protein in food.

The key discussion throughout this chapter is that green nanotechnology applied in conjunction with seaweed can provide an avenue of change and an effective solution to the global protein crisis. By using this modern technology, it is possible to develop a more resilient food system by developing a sustainable and circular system in which seaweeds act as value-added nanomaterials, which, in turn, would make protein production and nutrition more effective and sustainable. The chapter is organized to present a comprehensive picture of the biology and biochemical basis of seaweeds, the principles and mechanisms of the synthesis of nanoparticles, their characterization, use, and the important safety and regulatory issues that will underlie their implementation. The subsequent sections will methodically discuss this potential frontier, which maps a roadmap to tapping the power of the synthesized seaweed nanoparticles on the very big to feed the future.

2. Seaweed: Biology, biochemistry, and nutritional profile

The oceans of the world, occupying most of the surface of our planet, contain an immense and, to a large extent, unexploited reservoir of biological diversity, of which the seaweeds provide a subsistence and formidable resource. Several centuries of experience in consumption and traditional medicine have shown that seaweed has been used by people in the coastal regions as food and traditional medicine. Recent scientific studies have shown to uncover its enormous potential in solving modern-day issues of food consumption, nutrition, and sustainable food production (Habib et al., 2025). A detailed overview of seaweed biological classification, biochemical constituents, nutritional relevance, key processing challenges, and current technological strategies for optimizing its application as a protein source is summarized in Table 1. Seaweeds can be broadly divided into three major phyla, with their main distinction based on their unique pigmentation, which is a direct result of their evolutionary adaptations to varying light conditions in the marine environment. The red seaweeds (Rhodophyta) are usually in the deeper waters and have pigments such as phycoerythrin and phycocyanin, which enable them to take in the blue-green light that is absorbed (Freitas et al., 2022). Within this group are species of immense economic value, including Pyropia (nori) and Chondrus (Irish moss). The Phaeophyta, or brown seaweeds, tend to be of greater size and are found in cooler and shallower water, being brown due to the presence of the pigment fucoxanthin, and the common examples of them are Laminaria (kombu) and Macrocystis (giant kelp) (Najibi et al., 2025). Lastly, the Chlorophyta or the green seaweeds have a common ancestry with the inhabitants of land as they have chlorophyll a and b pigments and are often found in intertidal areas, with a notable example of Ulva (sea lettuce) (Saber et al., 2025). This taxonomic tripartite division is not simply a color issue, but a measure of big differences in the cellular structures, storage compounds, and, most importantly, in human applications and biochemical makeup (Pérez-Roa et al., 2025).

The real value of seaweed, in terms of nutritional and biotechnological value, is in its complex and diverse variety of bioactive substances. These are not simple nutrients but complex molecules that have been developed in the process of the algae surviving in a tough aquatic environment (Xie et al., 2024). These nutrients bring tremendous health benefits to the human body after consuming them. The majority of nutrients are the distinctive polysaccharides that constitute the structure of the algal cell walls. Alginates, which are linear copolymers of guluronic and mannuronic acid, form viscous gels in brown seaweed and help them to be flexible and strong against turbulent waves (Kenny et al., 2025). Agar and carrageenan are a family of red seaweed sulfated galactans, which are used in analogous structural functions, but are famous due to their extraordinary gelling, thickening, and stabilizing properties (Akter et al., 2024). These phycocolloids are not only used in the food industry, but their usefulness lies not only in texture, but in

Table 1 Summary of biological classification, biochemical composition, nutritional profile, challenges, and processing strategies for seaweed as a protein source.

Category	Subcategory	Key points/descriptions
Biological Overview of Seaweeds	Major Phyla	Rhodophyta (Red algae): Contain phycoerythrin and phycocyanin; thrive in deeper waters; economically important species include Pyropia (nori) and Chondrus. Phaeophyta (Brown algae): Larger in size; inhabit cool, shallow waters; pigmentation from fucoxanthin; includes Laminaria and Macrocystis. Chlorophyta (Green algae): Share ancestry with land plants; contain chlorophyll a and b; common species include Ulva.
	Ecological Adaptation	Pigmentation linked to light absorption at different depths; structural and biochemical diversification shaped by marine environmental pressures.
Biochemical Composition	Structural Polysaccharides	Brown algae: Alginates (guluronic & mannuronic acid copolymers) provide structural flexibility. Red algae: Sulfated galactans (agar, carrageenan) with strong gelling and stabilizing properties; act as dietary fibers with prebiotic potential.
	Proteins & Bioactive Peptides	Protein content varies across species; red seaweeds (e.g., Pyropia, Palmaria) are richest (up to 30–40 % dry weight). Proteins are rich in essential amino acids; enzymatic hydrolysis releases bioactive peptides with antihypertensive, antioxidant, and immunomodulatory effects.
	Pigments & Polyphenols	Accessory pigments such as fucoxanthin (brown algae) and phycoerythrin (red algae) exhibit antioxidant, anti-inflammatory, and anti-obesity properties. Brown seaweeds contain unique polyphenols (phlorotannins) with strong antioxidant activity.

Nutritional Profile of Seaweed	Protein Quantity	Highest in red algae (30–40 % DW), moderate in green algae, lower in brown algae.
	Protein Quality	Balanced essential amino acid profile; rich in aspartic and glutamic acid; contains good levels of lysine and methionine (often limiting in legumes).
	Additional Nutrients	High in dietary fiber; rich in minerals (iodine, calcium, iron, magnesium); contains vitamins (including B12—bioavailability still under study).
	Sustainability Advantages	Requires no arable land, freshwater, or fertilizer; contributes to carbon sequestration and nutrient remediation (mitigates eutrophication).
Challenges in Protein Utilization	Structural Barriers	Rigid cell walls with alginates, agar, and carrageenan restrict protein accessibility and digestibility.
	Antinutritional Factors	Polyphenols (e.g., phlorotannins) can bind proteins and digestive enzymes, forming complexes resistant to proteolysis.
	Mineral Overload	Excess iodine poses a safety concern if not properly controlled in processing.
	Sensory Barriers	Strong "marine," "fishy," or intense umami flavors limit acceptance in Western diets.
	Extraction Difficulties	Conventional extraction (heat, chemicals) often causes protein denaturation, low purity, and poor separation from polysaccharides and minerals.
Advanced Processing Technologies	Enzyme-Assisted Extraction	Utilizes cell-wall-degrading enzymes to release proteins efficiently; preserves functionality; food-grade and gentle.

(continued)

Table 1 Summary of biological classification, biochemical composition, nutritional profile, challenges, and processing strategies for seaweed as a protein source. (*cont'd*)

Category	Subcategory	Key points/descriptions
	Physical Disruption Technologies	Ultrasound-assisted extraction: Uses cavitation to break cell structures. Microwave-assisted extraction: Enhances heating efficiency and cell rupture for improved protein recovery.
	Membrane Filtration	Enables concentration and purification of protein fractions following extraction.
	Biorefinery Approaches	Integrate multiple methods to fractionate proteins, polysaccharides, pigments, and minerals into separate high-value components.
	End-Use Applications	Development of refined protein ingredients for incorporation into common foods (bread, pasta, meat analogues, beverages) to enhance protein content without sensory drawbacks.

their role as dietary fibers, able to withstand the actions of human digestive enzymes, as prebiotics, modulating gut microbiota to promote colonic health. In addition to these structural carbohydrates, seaweeds are a good source of proteins, peptides, and amino acids. Although the content is changeable, some red seaweeds, such as Pyropia, may contain just as much protein as traditional plant products such as soybeans (Pothiaraj et al., 2024; Sharma et al., 2025). In addition, these proteins not only contain all the essential amino acids, which makes them a complete source of nutrition. Also, the release of bioactive peptides in these proteins can be caused by the action of selected proteolytic enzymes, which have already demonstrated antihypertensive, anti-oxidant, and immunomodulatory activities in preliminary research.

Another bioactive compound is the pigment systems of seaweeds, which have been developed to efficiently absorb light and to protect against light. The accessory pigments, such as the fucoxanthin of the brown sea-weed and the phycoerythrin of the red seaweed are strong antioxidants with proven anti-inflammatory and anti-obesity effects in lab models

(Chini Zittelli et al., 2023). These pigments and a repertoire of polyphenolic compounds, including the phlorotannins, which are exclusive to brown algae, make up a powerful defense mechanism against oxidative stress, UV radiation, and herbivory. These compounds can have similar protective properties, scavenging the free radicals and reducing the risk of chronic diseases when included in the human diet. The overall nutritional value of seaweed, and in particular as a new and sustainable source of protein, is due to this complex of polysaccharides, proteins, and pigments (McKinney et al., 2025).

Seaweed as a future source of protein particularly bright due to the growing world population and the negative environmental impact of traditional livestock production. Protein is a highly species-specific component with the red seaweeds (red seaweeds tend to be the highest protein (up to 30–40 % of dry weight in some species like a Palmata)), next to the greens and the browns (Pereira et al., 2024). This protein is very quality sensitive, and it is relatively well balanced in terms of presentation of essential amino acids, and the profile of the protein is frequently quite good. The proteins with high aspartic and glutamic amino acid levels has an excellent lysine and methionine profile, which otherwise is usually deficient in legume proteins (Zhang et al., 2024). This makes seaweed an effective complementary protein that can be used to provide nutritional value to plant-based food. In addition to that, the protein is integrated into a complex of useful substances: dietary fibers, minerals (iodine, calcium, iron, magnesium), and vitamins (most of all, B12) to create a complete nutritional package (Łuszczki et al., 2023). The latter renders seaweed an activated food component, which can be used as a source of overall, as opposed to being solely a protein isolate, well-being and health. The sustainability attributes of seaweed farming further contribute to its attractiveness in that it does not require any land, freshwater, or fertilizer, and at the same time, it removes coastal eutrophication by sequestering carbon and preventing the erosion of the coastal environment (Pereira & Cotas, 2024).

The popularization of using seaweed protein is not an easy one. The same protective and structural polymers that render seaweed so useful are also very difficult when it comes to traditional methods of protein extraction and use. Physical barrier is the strong and complex cell walls, which are made up of undigestible polysaccharides such as alginates and carrageenans that restrict the bioavailability of intracellular proteins during human digestion (Ghelichi & Jacobsen, 2025). With these walls not properly destroyed, a large part of the protein could come out of the digestive system unabsorbed. Moreover, the biochemical composition of seaweed may have an adverse effect on the digestibility of proteins. Other species are sources of antinutritional factors that have the potential to combine with proteins and enzymes to form complexes that are resistant to proteolytic degradation, such as phlorotannins (Eladl et al., 2024). High mineral content, particularly iodine, although it is good in moderation, may pose an issue at high levels of ingestion and must be given care and processing to avoid any form of hazard. The unique and frequently intense flavor profile of a lot of seaweed, which is said to be umami, fishy, or marine, can be another obstacle that hinders consumer acceptance in Western markets, where it is not a standard food ingredient and therefore cannot be easily absorbed into mainstream foods (Vishwas et al., 2025).

These challenges require the establishment and utilization of superior and effective processing technologies. Traditional techniques such as hot-water extraction or chemical hydrolysis are not usually strong enough to completely destabilize the cell walls and may be harmful, resulting in protein denaturation, loss of functionality, or development of chemical remnants (Ganjeh et al., 2023). In addition, they tend to fail to selectively isolate the protein against the large concentrations of polysaccharides and minerals, thus producing a low-purity product. Thus, novel solutions are needed to unveil all the prospects of seaweed as one of the potential and high-quality sources of protein in the future. It should now concentrate on coming up with mild but efficient biorefinery methodologies capable of fractionating the valuable constituents of seaweed, namely proteins, polysaccharides, and pigments, into individual and high-value streams. New technologies, like enzyme-assisted extraction, which use enzymes targeted with a specific method to selectively hydrolyze cell walls and liberate proteins, have a lot of potential. Equally, ultrasound and microwave-supported extraction have the potential to physically damage cell structures in order to increase the efficiency of further protein reclaiming (Nunes et al., 2024). The protein fractions can then be concentrated and purified by membrane filtration technologies. The ultimate aim is to cease considering seaweed as a whole-food ingredient that can be marketed to niche markets and to use it as a sustainable raw material in the process of making refined, palatable, and highly bioavailable protein ingredients. This could then be easily added to a broad range of products that consumers already purchase, such as pasta and bread, meat analogues, and protein shakes, thus allowing consumers to continue enjoying the nutritional benefits of seaweed (Hofmann et al., 2025). Although the process of converting a raw and complex marine biomass to a refined and mainstream protein source is not without its technical issues, the biological, biochemical, and nutritional properties of seaweed have made a strong case for its use in creating a more sustainable and healthy food system in the next few decades.

3. Fundamentals of nanoparticle synthesis

The rise of nanotechnology has brought about a paradigm shift in science and industry, with activities that have never been possible before in terms of manipulating matter on an atomic and molecular level. Nanoparticles, which are generally specified as having one of their dimensions below 100 nanometers, are at the center of this revolution (Joudeh & Linke, 2022). The special optical, electrical, magnetic, and catalytic properties cannot be attributed to the material as such, but they are the direct result of their small size on the nanoscale. This large group of materials is generally distinguished in terms of composition. Silver, gold, or zinc-derived nanoparticles are also known for possessing a unique surface plasmon resonance that provides them with colorful and bright colors, since nanoparticles are efficient sensors, imaging, and antimicrobial agents (Çimen et al., 2025). In terms of stability and functionality versatility, metal oxide nanoparticles such as zinc oxide, titanium dioxide, and iron oxide play a key role in sunscreens, pigments, and catalysis, as well as drug delivery (Senthil Rathi et al., 2024; Sruthi et al., 2024). On the other hand, organic nanoparticles, including lipid-based, polymeric structures, proteinaceous structures, are typically sought after because of their biodegradability and biocompatibility, thus making them a good choice to use in encapsulating and targeted delivery of therapeutic agents in the pharmaceutical and food sectors (Ashfaq et al., 2023). Fig. 2 outlines the key steps and applications of seaweed-mediated green nanoparticle synthesis.

Synthesis of nanoparticles with the accurate control of their size, shape, and monodispersity is a prerequisite to being able to take full advantage of their potential. This has been done over decades by a set of traditional ways broadly defined as physical and chemical pathways. Physical approaches, which are also known as top-down approaches, are the mechanical milling or ablation of materials to form nanoscale pieces (Al-Harbi & Abd-Elrahman, 2025). Although these methods may generate nanoparticles without the

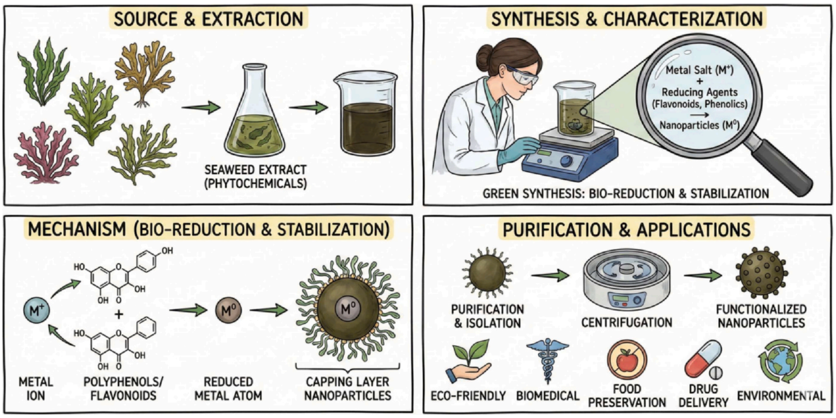

Fig. 2 Schematic overview of nanoparticle synthesis from seaweed. The figure outlines the major steps involved, including source and extraction of phytochemical-rich seaweed extracts, synthesis and characterization through bio-reduction and stabilization, mechanistic pathways involving metal-ion reduction by polyphenols and flavonoids, and the formation of capped nanoparticles.

complexity of solvent contamination, they are generally energy-intensive, involve complex instrumentation, and they tend to be unable to produce particles of uniform shape and a narrow size distribution. Similarly, the more commonly used ones are the chemical methods or the so-called bottom-up approaches, where the nanoparticles are prepared by the process of nucleation and selective growth of nanocrystals by the use of molecular precursors in solution (Abid et al., 2022). Chemical reduction, sol-gel processes, and co-precipitation are techniques in which finer control of the particle characteristics can occur. However, they are often based on dangerous reducing and stabilizing reagents, including sodium borohydride or hydrazine and volatile organic solvents. The application of these toxic chemicals casts serious doubts on environmental pollution, energy usage, and the likely presence of adverse residues remaining attached to the surface of the nanoparticle, which becomes very dangerous when it comes to biomedical and food-related purposes (Rajpal et al., 2025). Moreover, the difficulties and high expenses inherent in the waste management of the products of these synthetic pathways are significant economic and ecological constraints that remain in need of a solution.

To address these environmental and safety limitations of traditional synthesis, the field has become more oriented toward the concepts of green chemistry, leading to the emergence of the promising field of green synthesis (Walling et al., 2023). Green chemistry promotes the creation of products and processes that reduce or eradicate the use and production of dangerous materials. In nanoparticle synthesis, green synthesis aims to substitute the toxic chemical reagents with harmless biological extracts, solvent with water, and processes with low energy consumption, e.g. room-temperature reactions or solar-assisted synthesis (Hanna et al., 2025). There are numerous benefits of this method, and it is still more environmentally gentle, and it greatly decreases the production of toxic waste. Economically, it may prove cheaper through the utilization of easily available biological resources and a reduction in the purification processes. Importantly, to be used in medicine or nutrition, the nanoparticles prepared through green synthesis can be viewed as more bio-friendly, since they are surrounded by natural biological molecules as opposed to using synthetic compounds (Saxena et al., 2025). This capping layer is not a simple coating, but an active coating which gives stability to the colloidal suspension, and may have biologically effective properties of its own, like antioxidant or antimicrobial effects, which can be complemented by the inherent functionality of the nanoparticle core (Schubert & Chanana, 2018).

The green synthesis process only succeeds on the biological matrices used as nanofactories. These biological systems, including plants, algae, bacteria, and fungi, have a vast repertoire of metabolites that have the capacity to reduce metal ions and stabilize the resultant nanoparticles (Alawad & Kepekçi, 2024). A solution of a metal salt is combined with a biological extract, and the biochemical compounds of the extract help to reduce metal ions to their atomic zero-valent form, after which it is then subject to nucleation and growth into stable nanoparticles. These particular mechanisms are complicated and involve the function of biomolecules. Plant metabolites such as flavonoids, terpenoids, and phenolic acids are water-soluble and therefore also have hydroxyl and carbonyl components, which make them potent reducing agents (Elbouzidi et al., 2025). The proteins and amino acids not only help in reduction but also tend to bind to the new surfaces formed during the synthesis of the nanoparticle, thus preventing aggregation and ensuring stability. It is this bi-fold activity of decreasing and stabilizing that makes biological extracts so efficient (Kalantarian et al., 2025). Another very interesting avenue is presented by microorganisms, which use both intracellular and extracellular mechanisms. Certain bacteria and fungi have the capability to import metal ions into their cells, and the reduction process is carried out by enzymes such as nitrate reductases, whereas others release extracellular enzymes and polysaccharides that assemble and encapsulate nanoparticles in the medium around the cell (Cardoso et al., 2025). The deep strength of these biological matrices is that the synthesis reaction is a single-step synthesis, based in aqueous, which typically proceeds at ambient temperature and pressure, reducing the energy footprint of the synthesis by a factor relative to the traditional high-temperature or high-pressure approaches.

The study of the various biological sources of nanoparticles has demonstrated that seaweeds, as the object of our discussion above, are a very powerful and promising biological matrix. They are useful in this field as the direct outcome of the biochemical characteristics discussed above (Joicy et al., 2023). The large number of bioactive compounds contained in seaweed extracts, such as polysaccharides such as alginates and carrageenans, pigments such as phycoerythrin and fucoxanthin, proteins and peptides, and polyphenolic phlorotannins, offers a diverse and complicated combination of reducing, capping, and stabilizing factors (Hejna et al., 2024). The resultant biochemical diversity facilitates the easy preparation of a wide variety of metallic and metal oxide nanoparticles. As an example, the red seaweed polysaccharides with sulfate are capable of reducing the silver ions into stable silver nanoparticles, and the phenolic compounds in the brown seaweed can be used to synthesize the zinc oxide or iron oxide nanoparticles (Mansour et al., 2022). The existence of these varied functional groups implies that the parameters of the reaction, including the pH, temperature, the extract concentration, and the metal salt precursor, can be carefully adjusted to impose a certain level of control on the size, morphology, and quality of the resulting nanoparticles. Higher concentration of a stabilizing protein may produce different-shaped nanostructures; a slightly acidic pH could promote the activity of some of the phenolic groups, resulting in smaller particles (Jin et al., 2025). The relationship between the principles of nanoparticles production and the definite usage of seaweed extracts presents a new horizon for marine biomass addition. This method is a direct solution to the drawbacks of traditional chemical synthesis as it offers an ecologically friendly, sustainable, and economical option. Furthermore, it produces a strong overlap of the concept of nanotechnology and the search for sustainable protein sources. As such, the concept of green synthesis, even when implemented through a biologically versatile and sustainable resource, such as seaweed, goes beyond the synthesis of a nanomaterial.

4. Green synthesis of nanoparticles using seaweed extracts

Based on the principles of green synthesis, the use of seaweed extracts has become one of the most advanced and effective approaches to nanoparticle synthesis. The key biomolecular drivers, synthesis mechanisms, nanoparticle types, functional properties, and critical optimization parameters involved in seaweed-mediated green nanoparticle synthesis are summarized in Table 2. This adaptation of the complicated biochemical environment of a seaweed extract into a theoretical nanofactory, in which the various bioactive components work in a coordinated manner to lower metal precursors and stabilize the newly formed particles (Vemula & Chatragadda, 2025). The mechanism involved is an elegant one-pot reaction, which usually comprises the aqueous extract of seaweed with a solution of the required metal salt. The resultant change, which is usually observed by a change of color of the reaction mixture, is catalyzed by the redox chemistry of the metabolites of the seaweed (Dikshit et al., 2021). It is possible to conceptually divide the process into two important and simultaneous processes: reduction and stabilization. The first step is the gain of electrons by the metal ions in their ionic form, e.g. $Ag+$, or $Au+$, a process called nucleation. The excess of reducing agents that exist in the extract, such as hydroxyl and carbonyl groups of polyphenols, the sulfated groups of polysaccharides, and the electron-donating amino acids of proteins and peptides, is an efficient mediator of this reduction. These biomolecules share electrons, thereby decreasing the metal ions, thus starting the formation of atomic clusters (Yaraki et al., 2022). Fig. 3 summarizes green, bioinspired, and traditional approaches for nanoparticle synthesis and their major applications.

These atomic clusters are then increased by the addition of reduced atoms after nucleation, although without a stabilizing effect, these clusters would quickly form large and bulk precipitates (Belloni et al., 2020). This is where the second important role of the seaweed bioactives is required. A large variety of biomolecules, including long-chain polysaccharides and proteins, adsorb spontaneously on the growing nanoparticles. The formation of a capping layer forms a steric and electrostatic barrier that inhibits the actual contact of the nanoparticles and their aggregation, hence providing the nanoparticles with colloidal stability in suspension (Amiri & Behin, 2025). The place of certain groups of seaweed compounds is dominant in determining the effectiveness and success of this process. The

Table 2 Summary of mechanisms, biomolecules, nanoparticle types, functional properties, and optimization parameters in green synthesis of nanoparticles using seaweed extracts.

Category	Subcategory	Key points/detailed description
Fundamental Concepts of Green Synthesis	Green Synthesis Framework	Eco-friendly, single-pot, aqueous synthesis using seaweed extracts; relies on natural reducing and stabilizing agents; eliminates toxic chemicals and harsh processing.
	Reaction Overview	Metal salt solution + seaweed extract → visible color change; reduction of metal ions + stabilization of particles occurs simultaneously.
Mechanistic Steps	Reduction Phase	Metal ions (e.g., Ag^{+}, Au^{3+}) reduced to atoms by bioactive compounds; nucleation initiates formation of metal clusters.
	Stabilization Phase	Biomolecules adsorb onto nanoparticle surfaces forming steric/electrostatic barriers; prevent aggregation; maintain colloidal stability.
Seaweed Biomolecules Involved in Synthesis	Polysaccharides	Carrageenan (red algae) and alginate (brown algae) act as reducing and capping agents; long chains encapsulate nanoparticles and provide stability.
	Polyphenols	Phlorotannins (brown seaweeds) are potent reducing agents due to multiple hydroxyl groups; form dense capping layers.
	Proteins & Peptides	Amino, carboxyl, and thiol groups reduce metal ions and stabilize nanoparticles; can chelate metals; enable functionalization.

	Pigments	Compounds like phycoerythrin act as reducing agents; contribute to nanoparticle formation and coloration.
	Synergistic Effect	Multiple biomolecule classes act together, making crude extracts more effective than isolated compounds.
Nanoparticle Types Synthesized Using Seaweed Extracts	Silver Nanoparticles (AgNPs)	Rapid synthesis from $AgNO_3$; color changes to yellow-brown; show strong antimicrobial activity; used in coatings, medical textiles, and packaging.
	Gold Nanoparticles (AuNPs)	Produced from chloroauric acid; ruby-red appearance; highly biocompatible; used in biosensing, imaging, drug delivery.
	Zinc Oxide Nanoparticles (ZnO NPs)	Formed from zinc acetate/ nitrate precursors; excellent UV-blocking, antibacterial, and photocatalytic properties; applied in cosmetics and environmental cleanup.
	Iron Oxide Nanoparticles (Fe_3O_4, γ-Fe_2O_3)	Generated using Fe^{2+}/Fe^{3+} salts; magnetic properties enable drug targeting, MRI contrast enhancement.
	Titanium Dioxide Nanoparticles (TiO_2 NPs)	Synthesized from Ti precursors; eco-friendly photocatalysts for degradation of pollutants.
	Composite/Protein-Functionalized Nanoparticles	Seaweed proteins form external corona; produce bio-hybrid nanomaterials with enhanced biocompatibility, targeted delivery, and intrinsic biological activity (antioxidant, antihypertensive).

(continued)

Table 2 Summary of mechanisms, biomolecules, nanoparticle types, functional properties, and optimization parameters in green synthesis of nanoparticles using seaweed extracts. (*cont'd*)

Category	Subcategory	Key points/detailed description
Functional Properties & Applications of Seaweed-Derived Nanoparticles	Biomedical Applications	Antimicrobial coatings, wound dressings, drug delivery systems, anticancer potential, biocompatible agents for imaging.
	Environmental Applications	Water purification, photocatalysis (TiO_2, ZnO), pollutant degradation, antimicrobial surfaces.
	Industrial & Nutraceutical Uses	Food packaging, UV protection materials, biosensors, fortified supplements, functional coatings.
	Optical & Magnetic Properties	AuNPs: surface plasmon resonance for sensing; Fe_3O_4: magnetic manipulation and imaging.
Reaction Parameters Influencing Synthesis	pH	Controls ionization of biomolecules; alkaline pH enhances phenolic reduction; affects nucleation rate, particle size, and uniformity.
	Temperature	Higher temperatures accelerate kinetics; moderate heat improves reduction; excessive heat denatures proteins and destabilizes nanoparticles.
	Seaweed Extract Concentration	Determines availability of reducing/capping agents; higher concentration → smaller, more stable nanoparticles; too low → incomplete reduction.

	Metal Precursor Concentration	Controls number of nucleation sites; excess ions cause aggregation; optimal metal-to-extract ratio is essential for monodispersity.
	Reaction Time	Longer times allow growth and maturation of nanoparticles; influences morphology and crystallinity.
	Species-Specific Variability	Different seaweeds contain varying amounts of proteins, phenolics, and polysaccharides; affects synthesis pathways and particle characteristics.
Advantages of Seaweed-Based Green Synthesis	Ecological Benefits	Renewable biomass; no toxic reagents; energy-efficient; minimal waste; environmentally benign.
	Biochemical Richness	Multitude of natural reducing/capping agents provides superior efficiency; allows synthesis of uniform and functional nanoparticles.
	Biocompatibility	Protein- and polysaccharide-coated nanoparticles show enhanced safety for biomedical use.
	Tunability	Reaction conditions can be adjusted to engineer nanoparticles with specific sizes, shapes, and functions.
Challenges and Considerations	Extract Variability	Natural variability in composition affects reproducibility; requires standardization.

(continued)

Table 2 Summary of mechanisms, biomolecules, nanoparticle types, functional properties, and optimization parameters in green synthesis of nanoparticles using seaweed extracts. (*cont'd*)

Category	Subcategory	Key points/detailed description
	Need for Optimization	pH, temperature, and concentration must be systematically tuned for each seaweed species and metal precursor.
	Scalability Issues	Complexity of biological extracts can pose challenges for industrial-scale nanoparticle manufacturing.
	Characterization Requirements	Requires advanced analytical tools (TEM, SEM, UV–Vis, FTIR) to confirm size, morphology, and biomolecule binding.

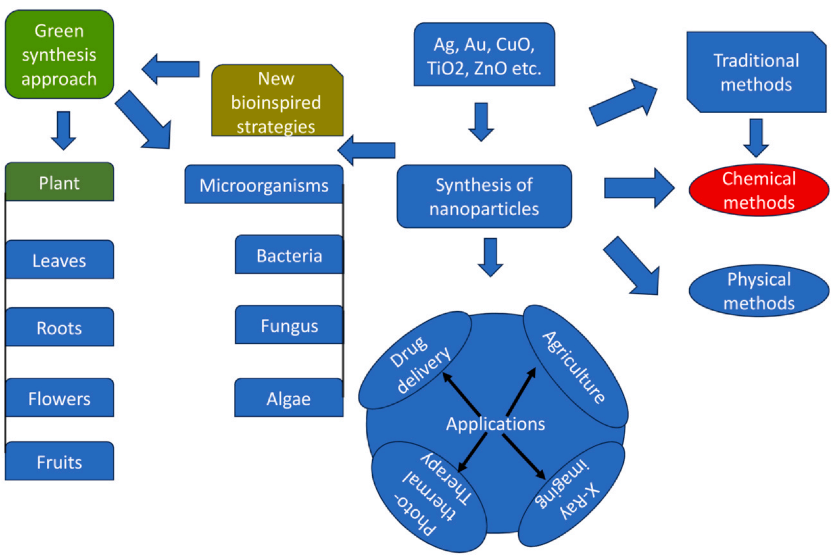

Fig. 3 Overview of green and conventional approaches for nanoparticle synthesis and their applications. The diagram contrasts plant- and microorganism-based green synthesis and new bioinspired strategies with traditional chemical and physical methods.

sulfated polysaccharide, including carrageenan found in red algae and alginate found in brown algae, is not a passive stabilizer. The functional groups may also be involved in the process of reducing metal ions, and the long polymer chains can effectively encapsulate the nanoparticles (Atik et al., 2025). Equally, phenolic compounds such as the phlorotannins, which are highly abundant in brown seaweeds, are highly potent reducing agents as a consequence of their numerous hydroxyl groups and also because they form very thick coats over nanoparticle surfaces (Pereira & Cotas, 2023). Even the pigments and proteins play a major role; phycoerythrin can serve as a reducing agent, and proteins are a source of amine and carboxyl groups that chelate the metal ions and cap the particles (Tan et al., 2023). It is such a complex interaction of various classes of bioactives in the crude extract that makes seaweed an excellent and multifaceted green synthesis that can often outperform systems that utilize one purified compound.

These mechanisms can be used in practice to produce a wide range of nanomaterials. The best studied are the metallic nanoparticles, especially silver and gold, because their synthesis is relatively easy and also because of their powerful application (Zuhrotun et al., 2023). The addition of a solution of silver nitrate to a seaweed extract is most frequently rapidly reduced to produce silver nanoparticles, which is often accompanied by a change in color to a typical yellowish-brown (Eker et al., 2025). These silver nanoparticles, which are bio-generated, have been found to be very effective in antimicrobial activity against a variety of pathogenic bacteria, and their application in medical devices and as packaging material in food products is evident (Sati et al., 2025). Chloroauric acid is synthesized into gold nanoparticles, which are normally of ruby-red color and are highly desired on the basis of biocompatibility and optical unconventionality, thus making them suitable in biosensing and drug delivery systems (Khan et al., 2022). In addition to the noble metals, it has been observed that extracts of seaweed can be used to produce nanoparticles of vital metals such as zinc and iron. The production of these particles frequently results in the development of a metal oxide shell, or could be directed towards the generation of pure metal oxide nanoparticles. An example would be the use of zinc acetate or zinc nitrate precursors that can replicate with seaweed extracts to produce zinc oxide (ZnO) nanoparticles, which are semiconductor materials that block UV light and have very good photocatalytic capabilities (Alprol et al., 2023).

Production of metal oxide nanoparticles by seaweed is a relatively fast-moving frontier. Iron oxide nanoparticles can be synthesized using iron salt precursors and seaweed extracts abundant in reducing polymethoxylenes. For example, magnetite (Fe_3O_4) and maghemite ($^6Fe_2O_3$) (El-Kassas et al., 2016; Ganapathe et al., 2020). These magnetic nanoparticles are also of great promise in targeted drug delivery, in which case an external magnetic field can cause the magnetic nanoparticles to target a particular location within the body, or magnetic resonance imaging (MRI) contrast enhancement. Likewise, green synthesis of titanium dioxide (TiO_2) nanoparticles with seaweed extracts is an emergent market with a view to developing photocatalyst systems to clean up the environment based on greener alternatives to the traditional chemical synthesis (Alarif et al., 2023). The actual skill of utilizing a biologically complicated matrix, such as seaweed, however, is the capacity to make advanced composite and protein-functionalized nanoparticles. The synthesis process can be used to generate nanoparticles that are naturally functionalized with a corona of seaweed proteins and peptides by choosing seaweed species rich in proteins, or using protein-rich fractions of an extract as starting material in the synthesis process. This is an in-situ functionalization that forms a bio-hybrid material in which the core of the inorganic nanoparticle is synergistically coupled with the bioactivity of the protein shell. Not only is such a particle a nanocarrier but an active therapeutic or nutraceutical agent, in which case the protein coating might provide superior biocompatibility, targeting properties, or even inherent biological function, such as antioxidant or antihypertensive activity (Gressler et al., 2025).

The green synthesis process requires careful optimization of various critical reaction parameters in order to ensure the effectiveness and reproducibility of these processes. Contrary to the traditional method of the chemical synthesis of the pure reagents, the dynamic character of a biological extract demands a methodical strategy of controlling the size, form, and distribution of the nanoparticles. The PH of the solution to be used in the reaction is also something that should be considered, as that will determine the ionization and reducing ability of the bioactive compounds (Alfaid et al., 2024). Such a slightly alkaline PH will probably promote deprotonation of the phenolic groups of phlorotannin, which would probably raise their electron-giving capacity and accelerate their rate of reduction and possibly reduce the diameter of the nanoparticles. Instead, other groups of compounds could also be active at pH that is acidic and exhibit different nucleation and growth behavior. The other lever that is powerful is temperature, since the greater the temperature of the reaction, the greater the kinetic energy of the molecules, and the greater its rate of reduction (Koçer & Özçimen, 2025). However, it is a two-edged sword. Heat above a moderate level may lead to the denaturation of proteins and other stabilizing elements in the extract, thus leading to uncontrolled growth and aggregation of particles at a high rate, and thus destroying the monodispersity of the final product.

The concentration of reactants is also of principal influence. The concentration of reducing and capping agents is conditional on the concentration of the seaweed extract. The higher the level of extract, the larger will be the rate of reduction, as well as the denser will be the capping layer that is obtained, and the smaller will be the nanoparticles, and the more stable will be the nanoparticles (Villagrán et al., 2024). On the contrary, the quantity of metal salt precursor defines the quantity of nucleation sites. The proportion of the metal salt to the extract is significant; excess of metal ions is likely to cause saturation of capping the extract, causing formation of polydispersed particles and their aggregation, whereas too little concentration will lead to low yield (Kocer & Özçimen, 2022). Therefore, the way to generate transparent nanoparticles using seaweed extracts is trial and error, and the pH, temperature, and concentration are carefully considered to find the optimal environment of a certain species of seaweed and a particular type of nanoparticle. It is a systematic tuning that allows the researcher to move beyond simply synthesizing nanoparticles to engineering nanoparticles with desirable characteristics that open their application in more significant ways (Das & Paul, 2025). This green paradigm of synthesis, where only renewable resources, a metabolically diverse resource, the seaweed is used towards sustainable nanotechnology, the creation of functional nanomaterials with a small environmental footprint, as well as contributes to giving the marine biomass an added value.

5. Characterization of seaweed-synthesized nanoparticles

Nanoparticle synthesis using seaweed extracts is effective, as its successful synthesis is indicated by the change of color in the reaction mixture, but it does not mark the end of the scientific work. A strict and multidimensional definition is therefore a requirement to be conversant, contend, and eventually harness such nanoscale materials. This phase of the study is even greater than formation creation, and it advances to a greater level of work of shaping the physicochemical character of the nanoparticles, and this stage would reveal substantial data that would correlate the structural properties and the approachable future application and security of nanoparticles (Ponnuchamy & Jacob, 2016). The first goal is to arrive at a detailed description of the particles that have been synthesized to give some basic answers to some of the questions, such as the size, shape, the internal structure, as well as the surface chemistry and purity as a whole. An array of multifaceted spectroscopic and microscopic methods is applied in this analytical adventure, with each of them offering a new view of the nature of the nanoparticle. This lack of original characterization would lead to applications or biological testing later in this regard that would solely be based on thin air, as the efficacy of nanoparticles, catalytic capacity, antimicrobial activity, or cellular interactions would be at the order of these physical and chemical properties (Bandyopadhyay et al., 2012). Fig. 4 outlines the key analytical and biocompatibility assessments used to validate seaweed-synthesized nanoparticles.

The most intuitive types of nanoparticles are microscopy, in which the nanoparticles can be observed directly, and therefore allow making the most intuitive conclusions. This is especially important in the case of such techniques as Transmission Electron Microscopy (TEM) or Scanning Electron Microscopy (SEM), which are considered to be the eyes of the world of nanoscopic dimensions (Eppler et al., 2000). By passing a beam of electrons through a very thin sample, TEM can give high-resolution, two-dimensional images that can be used to determine the exact size, morphology, and internal structure of single particles. It is able to clearly differentiate between balls, cylinders, triangles, and other geometrical shapes that might have been created in the course of the synthesis (Chithrani et al., 2006). SEM, alternatively, is used to scan a directed beam of electrons on the sample surface to obtain detailed topographical images in 3D, which are useful in measuring the surface texture as well as the overall dispersion of the nanoparticles and whether they are made of individual particles or whether they have formed larger aggregates. Such microscopic studies are essential as they offer the initial direct proof of effective nanofabrication. The product comprises spherical silver nanoparticles with an average diameter of 25 nanometers, as opposed to disordered microparticles or bulk precipitate (Smetana et al., 2005). In addition, they confirm the applicability of the capping agents in the seaweed to prevent aggregation, which is a significant determinant of colloidal stability and effective functioning.

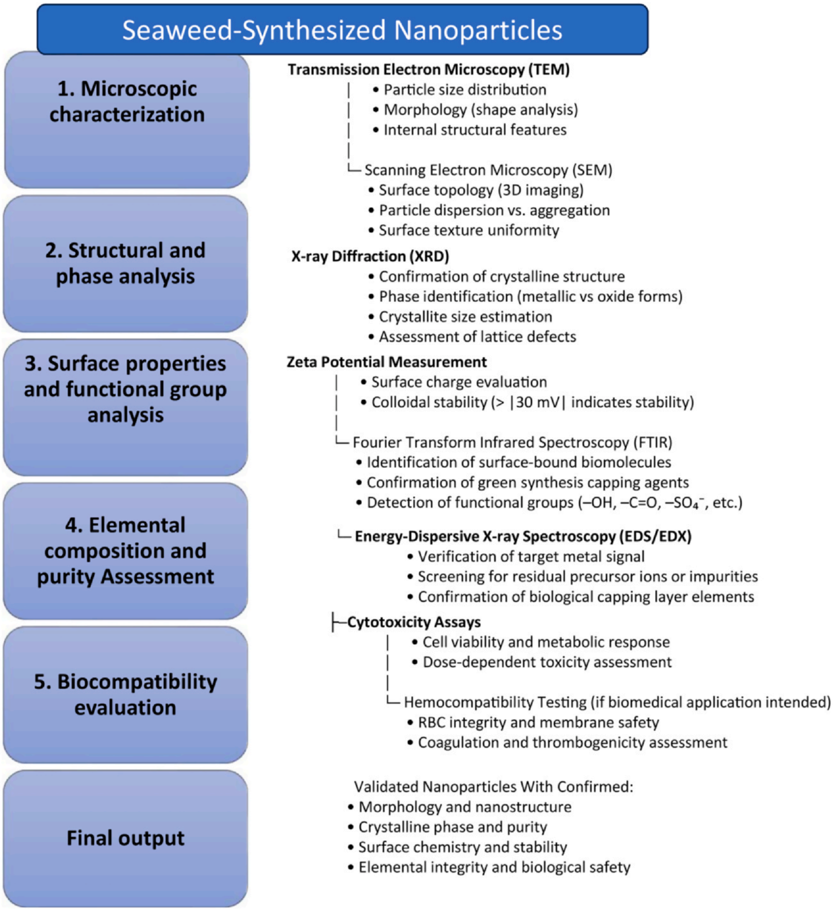

Fig. 4 Workflow outlining the comprehensive evaluation of seaweed-synthesized nanoparticles.

Even though microscopy can be applied in order to examine the exterior shape, other techniques must be employed to examine the interior structure and crystalline structure of the nanoparticles. One such effective workhorse is X-ray Diffraction (XRD), which is an indicator of crystallinity in a material (Abotaleb et al., 2024). After a beam of X-rays is exposed to a powdered sample of the nanoparticles, it diffracts in a pattern that is characteristic of the atomic structure in the crystal lattice. The resulting diffractogram and its characteristic peaks may be tabulated against known standards to unequivocally determine the chemical composition and phase of the nanoparticles, distinguishing, e.g., between metallic silver and silver oxide, or the various forms of crystallinity of titanium dioxide. The XRD peaks may give an indirect indication of the mean size of the particles, and also show the existence of structural defects because their sharpness and width can also indicate the presence of structural defects. This information is vital, and the crystalline phase may have a dire effect on such characteristics as catalytic activity, electronic structure, and chemical stability. A nanoparticle identified by XRD to be pure, crystalline magnetite (Fe_3O_4) has the magnetic properties required in biomedical applications (Groß et al., 2013).

The analysis of the surface is the most revealing description of the green-synthesized nanoparticles; the point of contact between the nanoparticles and the surrounding environment. The Zeta Potential, which is a measure of surface charge, is an important measure of colloidal stability (Clogston & Patri, 2011). It is a measurement of the electrical potential of the slipping plane of the particles suspended in a solution. The large absolute value of zeta potential (usually the absolute value of zeta potential is more than 30 mV) indicates that the individual nanoparticles are strongly repelled by each other due to their negative charges. Therefore, they do not form aggregates and have a long life. Such a charge is a direct product of the ionizable functional groups of the capping agents of seaweed. Fourier-Transform Infrared (FTIR) Spectroscopy is used to determine these particular chemical groups (Sun et al., 2000). The FTIR analysis is based on passing the infrared radiation through the sample and measuring wavelengths that are absorbed by the sample, which are related to the vibrational energy of certain chemical bonds. The spectrum that results is a molecular fingerprint, which demonstrates the existence of carbonyl functions in proteins, hydroxyl functions in polyphenols, sulfated functions in carrageenan, and additional functional indications in the seaweed extract that are currently linked to the nanoparticle surface. This is conclusive evidence of the mechanism of green synthesis, which shows that the biomolecules do not simply exist in the solution but are directly attached to the nanoparticles and form the stabilizing surface, which determines the biological interactions of the nanoparticles.

Although confirmation of biocompatibility and purity may not be the most important step in characterization, especially when the end intended use is in food, medicine, or agriculture, it remains the last and most crucial phase of characterization. This will entail a number of assays that will target the interaction of the synthesized nanoparticles and the biological systems to not only be effective but also to be safe. The initial procedure tends to be purity testing against inorganic contaminants, and one of the methods that can be used is Energy-Dispersive X-ray Spectroscopy (EDS or EDX) with SEM or TEM (Abdul Rahman et al., 2025). EDS represents a spectrum of the sample, producing an elemental decomposition that both verifies the target primary metal (strong silver signal, etc.) is present and shows any potentially toxic leftover ions of the precursor salts or other elemental impurities to the synthesis. A clean EDS spectrum, where the only peaks are those of the desired element and the ones of the biological capping layer (carbon, oxygen, sulfur), is a great indicator of a pure product.

However, biocompatibility does not necessarily come with the lack of inorganic contaminants. This should be proactively proven by means of biological tests. The basis of this evaluation is cytotoxicity assays. Such experiments are usually in vitro experiments in which the use of existing human or animal cell lines is performed, where cells are subjected to different levels of concentration of the seaweed-synthesized nanoparticles (Viswanathan et al., 2024). Exposure to colorimetric or fluorescent markers allows researchers to measure cell viability, cell proliferation, and overall cell metabolic activity. Bio-compatible nanoparticles will have little or no toxicity, and cells will be able to grow at a reasonably high concentration. This is an important distinction from chemically synthesized nanoparticles that can be toxic because of the leftover reagents. The advantageous nature of the synthesis of seaweed is inherent in the fact that the capping layer is made of natural compounds, many of which are food-grade, which, in general, will enhance a more desirable toxicological profile. Moreover, the hemocompatibility of the nanoparticles, i.e., their interaction with blood constituents, can also be examined so that they do not cause red blood cell rupture or clotting, which is necessary in the case of any intravenous use (Mares Briones et al., 2025). Collectively, this complete collection of characterization methods, including the visualization of form with microscopy, the determination of the crystalline structure with XRD, the surface chemistry with FTIR and Zeta Potential, and finally the safety of synthesis by means of a series of biocompatibility tests, turns what was initially a triumph of synthesis by observation into a solid, data-supported platform. This stringent procedure is what has made seaweed-produced nanoparticles viable and promising products to be used in the further generation of technological and therapeutic products.

6. Applications in enhancing protein nutrition

Green-synthesized nanoparticles and nutritional science cross a revolutionary horizon, especially in the field of protein nutrition. With a developed set of procedures for preparing and defining the use of these special nanomaterials of seaweed, it follows naturally and powerfully to consider the applications of these new materials in the improvement of our dietary protein utilization, absorption, and benefit (Abuzeid et al., 2023). The potential roles, mechanisms, and sustainability benefits of seaweed-derived nanoparticles across agricultural and aquaculture protein production systems are summarized in Table 3. The process where a nutrient is absorbed after intake to the ultimate site of action in the body is full of difficulties, and in the case of most bioactive compounds, including certain amino acids and peptides, this process is impeded by low solubility, instability in the tough environment of the gastrointestinal tract, and low permeability across the intestinal surface. Here, the special characteristics of the nanoparticles produced by seaweed come into play, and it is possible to place them as advanced and biocompatible systems of nanoparticles that, in turn, deliver nutrients. Their small sizes on the nanoscale and functionalized surfaces enable them to work as protective molecular escorts to delicate protein-derived nutrients (Nunes et al., 2025).

The application is concerned with the principle of increased bioavailability. Nanoparticles have the potential to significantly boost the fraction of absorbed nutrients consumed across the gut mucosa and ingested into the systemic circulation with their therapeutic effect (McClements & Xiao, 2017). This is especially applicable to the nutrition of proteins, where it is not only the absorption of the essential amino acids, but also larger functional peptides that are important. The derivatives of these nanoparticles are capping agents that are seaweed that do not stabilize the particle but can also make it closer and more vulnerable to cellular ingestion processes (Vitulo et al., 2022). This level of nutrient delivery used to be the prerogative of costly pharmaceuticals, but with the application of green nanotechnology, it is now being pursued as a strategy of option in functional foods and nutraceuticals and is bound to provide the most nutritional bang for the buck of protein consumed.

Other weaknesses of different plant and alternative proteins are low solubility, aggregation-prone, low emulsion and foam-forming, and stabilizing properties. These functionality characteristics are vital in the production of items such as smooth drinks, stable salad dressings, or fluffy cakes

Table 3 Applications of seaweed-synthesized nanoparticles in sustainable protein production systems.

Application area	Problem addressed	Role of seaweed-based nanoparticles	Mechanism of action	Expected outcome / benefit
Precision Agriculture (Legume Production)	Low nutrient-use efficiency, fertilizer waste, poor nitrogen fixation, abiotic stress	Nano-biofertilizers (Zn, Fe, Mo) and nano-pesticides	Controlled nutrient release; improved uptake due to nanoscale size; sustained protection of active ingredients; enhanced plant–microbe (rhizobia) interactions	Increased seed yield and protein content; reduced chemical inputs; improved nitrogen fixation and stress tolerance
Crop Protection	Excessive pesticide use, environmental contamination, pest resistance	Nano-pesticides with encapsulated actives synthesized via seaweed extracts	Targeted delivery; slow release; enhanced surface adhesion; rain-resistant application	Reduced pesticide dosage; decreased ecological impact; improved crop resilience
Aquaculture Disease Management	Frequent disease outbreaks (e.g., *Vibrio*, *Aeromonas* spp.); high antibiotic dependency	Silver and zinc oxide nanoparticles synthesized using seaweed extracts	Antimicrobial action; immune-stimulatory effects via feed inclusion or immersion treatment	Lower mortality; reduced need for synthetic antibiotics; improved immune function
Aquaculture Feed Efficiency	Nutrient leaching, low conversion efficiency (FCR), environmental pollution from unused feed	Nano-encapsulation of amino acids, vitamins, attractants	Reduced nutrient loss; higher bioavailability; improved absorption in gut	Lower feed input for same biomass; reduced waste; increased protein production efficiency

(continued)

Table 3 Applications of seaweed-synthesized nanoparticles in sustainable protein production systems. (*cont'd*)

Application area	Problem addressed	Role of seaweed-based nanoparticles	Mechanism of action	Expected outcome / benefit
Seaweed-Nanocomposite Biofertilizers	Inefficient organic soil amendments; inconsistent stimulation effects	Composite of powdered seaweed + seaweed-derived nanoparticles (ZnO/Fe_2O_3)	Dual action: organic biostimulation (betaines, polysaccharides) + nanoparticle-mediated micronutrient delivery	Improved soil health, root development, enzyme activity (photosynthesis, nitrogen metabolism), and crop tolerance to drought/salinity
Circular Bioeconomy Model	Linear resource usage and waste generation in food systems	Recirculation of marine biomass into agriculture through nanotechnology	Value-added conversion of seaweed into functional nanomaterials and fertilizers	Closed-loop sustainable food production and reduced dependency on synthetic agrochemicals

(Nesic et al., 2024). One of the solutions to these challenges could be the direct integration of special nanoparticles. To illustrate, nanoparticles with polysaccharide caps or silica cores can also be used to interact with protein molecules, destabilizing large protein aggregates and exposing more hydrophilic functional groups to the water, and enhancing the solubility of proteins in a dramatic fashion. This increased aqueous solubility is a necessary requirement of practically every other functional activity in a liquid food matrix. Likewise, in emulsified products such as mayonnaise substitutes or sauce, nanoparticles may penetrate the oil-water interface, forming a solid protective barrier between the oil droplets, which then prevents oil droplet coalescence (Quarato et al., 2024). The resulting effect is called Pickering stabilization, and it produces emulsions that are extremely resistant to creaming and separating, and in many cases, they are more effective than traditional molecular emulsifiers. The result will be enhanced shelf life and texture of a product.

Naturally, the alteration of these simple properties leads to fortification and production of new foods that are high in protein. The food industry is being forced to develop alternatives to the traditional staples because of the necessity in the international world to seek sustainable sources of protein (Pereira et al., 2024). Nanoparticles generated through seaweed offer a channel for incorporating better nutrition into such new product matrices. The most interesting, perhaps, indirectly, the nanoparticles themselves can be a source of important minerals; nanoparticles of zinc oxide or iron oxide synthesized with seaweed could enter food fortification, resolving common deficiencies of micronutrients and possibly being more bioactive than conventional mineral salts. This is not simply the case of supplementation, but it enables the creation of what can be termed intelligent food systems, where the nanomaterial is not considered an additive but a multi-purpose entity that improves texture/stability/nutritional density at the same time (de Souza Celente et al., 2023).

The intensive livestock industry is constantly strained in order to improve the growth rate of the animals, their health, as well as their feed ratios, and reduce the reliance on antibiotics and other artificial enhancers. Nanoparticles produced by seaweed are a potentially valuable natural resource to overcome these issues in animal feed (Morais et al., 2020). They can improve the bioavailability of important amino acids such as lysine and methionine in monogastric animals such as poultry and swine, since they serve as vehicles of nutrient delivery. Nanoparticles ensure a more efficient and targeted delivery of these important nutrients to the bloodstream, which can lead to better growth performance and lean muscle development by preventing their destruction during the feed or during the upper digestive tract. The same technique can be used to deliver vaccines, vitamins, or any other therapeutic to improve the health of animals and minimize mortality (Raja et al., 2022).

In addition, some nanoparticles, especially those of silver or zinc oxide, have well-reported antimicrobial properties. Added to the feed, they have the potential to be used as growth promoters by balancing the gut microbiota, inhibiting pathogenic microbes, and enhancing a healthier intestinal environment (Jomehzadeh et al., 2021). This may result in a decrease in disease occurrence and decreased use of prophylactic antibiotics, which is one of the major measures to fight antimicrobial resistance (Oh et al., 2024). The fact that these nanoparticles are produced naturally, using green resources, i.e., seaweed, is also a major plus in this regard because it is in line with the current consumer demand in relation to the natural and sustainable production systems of animals (Morais et al., 2020). The enhancement of the functional properties of feed proteins by the nanoparticles also cannot be neglected. The nanoparticles may positively affect the quality of the pellets, the dust reduction, and the overall homogeneity of the feed, which will reduce the amount of waste and guarantee a more stable intake of nutrients to the animals. This technology will combine the power of the ocean to create a more resilient, efficient, and health-oriented food system in the future by enabling the targeted delivery of bioactive peptides in human nutraceuticals, extending the stability of the next generation of plant-based foods.

7. Applications in sustainable protein production systems

Fig. 5 highlights the role of seaweed-derived green nanoparticles in enhancing nutrition, health, and sustainability. One of the key applications in this area is the synthesis of nanobifertilizers and nano-pesticides, which are specifically meant to augment the planting of basic protein foods like legumes (Gade et al., 2023). Legumes, having the special faculty to fix nitrogen in the atmosphere by symbiotic relations with rhizobia bacteria, are the keystone of the global supply of proteins (Saleem et al., 2024). Abiotic stresses and nutrient deficiencies, however, tend to limit their productivity. Traditional fertilizers are especially poor in their efficiency, and much of the nutrients

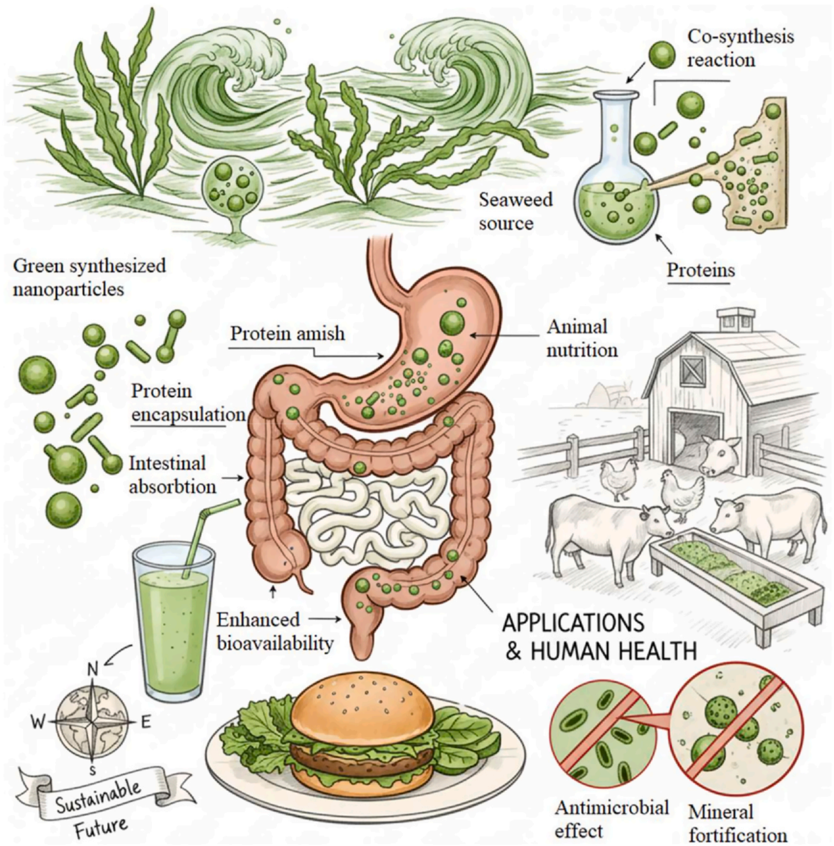

Fig. 5 Illustration of the potential applications and health benefits of seaweed-derived green nanoparticles across the food and nutrition continuum.

deposited are washed away, resulting in eutrophication or the conversion to greenhouse gases. This issue is addressed by nano-biofertilizers that entrap the micronutrients (such as zinc, iron, or molybdenum) in a nanoscale carrier. Controlled release of these nanoparticles, frequently produced by synthesis using seaweed extracts, which in turn are produced by biostimulatory compounds, can be engineered (Miranda et al., 2024). Their small size and high surface area help them to be easily absorbed by the plant roots or leaves, making sure that a larger percentage of the nutrients is actually absorbed by the plant's target. This accurate application could significantly boost the health of the plants, the effectiveness of nitrogen fixation, as well as the end result of increased yields of seeds with high protein content. Equally, nano-pesticides, in which the active constituents are contained in a protective nanocarrier, can offer increased tailored and rain-resistant control of pests, reducing the amount of chemicals used, and limiting environmental incursions (Forest et al., 2025). Nanotechnology will allow making nutrient and pest management more efficient, which will allow cultivating more robust and productive legume crops, which will support the plant-based protein pipeline right at the start.

The concept of sustainable production is equally important in the aquatic world, where aquaculture has come to be an irreplaceable source of animal protein for an increasing world population. Nevertheless, intensive aquaculture is not devoid of its own sustainability issues, such as the outbreak of diseases, water contamination by Hong Kong feed, and the use of fishmeal that is based on wild-caught stocks (Yue et al., 2024). Seaweed-produced nanoparticles integration offers new solutions to these long-standing problems and improves the health of the grown species, as well as increases the efficacy of their food. Among the most promising applications of these nanoparticles, this is regarded as an alternative to antibiotics and synthetic therapeutics in the management of fish health. When prepared through seaweed, the well-documented antimicrobial effects of silver or zinc oxide nanoparticles are realized as a natural and, perhaps, less harmful method of control of pathogenic bacteria such as Aeromonas hydrophila and Vibrio species, which can result in catastrophic losses in fish and shrimp farms (Das & Paul, 2025). The administration of these nanoparticles can be done by immersion baths or they can be added to the feed through which they can stimulate the immune system of the aquatic animals in a systematic manner (Liu et al., 2022).

In addition to disease control, nanoparticles can be used to specifically solve the issue of feed efficiency, which is a significant economic and environmental issue in aquaculture. Much of the traditional aquaculture feed is wasted and dissolved into the water column, and is then fed upon, leading to nutrient pollution (López-Mayán et al., 2024). Nano-encapsulation of feed components, e.g., essential amino acids, vitamins, attractants, etc., may form a shield-like layer reducing leaching of nutrients (Awuchi et al., 2022). This is so that a greater proportion of the costly and resource-consuming feed is actually consumed by the fish. Moreover, the bioavailability of the nutrients enhanced by the nanoscale delivery system implies that the nutrients are more easily absorbed in the gut, which increases the feed conversion ratio, i.e., the ratio of the feed required to generate one unit of weight gain. This mixed-purpose effect of minimizing waste and enhancing assimilation implies that it will use less feed to generate an equivalent quantity of fish protein, which will reduce the cost of production and the ecological footprint of the production (Bunglavan et al., 2022). The sustainability and productivity of the aquaculture industry, an important component of food security in the future, can be greatly promoted through the introduction of green nanoparticles to enhance a healthier stock and better utilization of the resources available.

Probably the most attractive use of this technology is in the synthesis of synergistic composites, which reduces back to the original material, the seaweed in the first place. The idea is to develop high-order agricultural products consisting of whole seaweed or extract, and the nanoparticles made out of the same, and associate them to form a potent biostimulant in crop production on land (Sharma et al., 2025). The application of seaweed as a soil conditioner dates back centuries, though it may be erratic and its mechanism of action complicated. This natural biostimulation can be sharpened and enhanced by the introduction of nanoparticles. An example is a composite material that has been designed based on a base of powdered Sargassum or Kappaphycus seaweed, laced with zinc oxide or iron oxide nanoparticles, which were also produced using an extract of the same seaweed (Nirmalkar et al., 2023). This forms a self-supporting mechanism. The seaweed matrix is a source of good macronutrients, organic materials, and typical biostimulatory substances such as betaines and polysaccharides. It improves the soil structure and mobilizes beneficial microbial ecosystems. These carried nanoparticles, in their turn, provide a highly bioavailable controlled-release source of necessary trace metals that are in high demand in the enzyme systems of plants associated with photosynthesis, nitrogen metabolism, and stress tolerance (Kumar et al., 2024).

An example of a seaweed-nanoparticle composite applied to a leguminous crop would be applied on multiple purposes. The organic part would ensure the growth of roots, and the symbiotic rhizobia and nanoparticles would ensure constant and efficient delivery of micronutrients directly to the plant, which would address any deficiencies that would otherwise limit protein synthesis and seed growth (Zafar et al., 2024). This is not a mere fertilization process but a complete biostimulating process that improves the physiological processes of the plant. The side effect is that this results in an increased yield crop, but also makes it more tolerant to the environment, such as drought or salinity, a characteristic that is becoming more important with climate change. This is the embodiment of the values of a sustainable bioeconomy in that a circular process, where value-added nanomaterials are created through the use of seaweed, endows other agricultural systems, in effect, enhancing their functionality. It indicates that the technological silver bullet is not the solution to the future of protein production, but an intelligent combination of biological resources and nanoscale engineering (El-Nablaway et al., 2024). Combining the natural potential of the marine biomass and the green nanotechnology, we would be capable of devising some powerful devices to feed the crops and the grown species, which would feed mankind back, and would make the food system a little stronger and more productive.

8. Safety, toxicity, and regulatory considerations

The enormous potential of nanoparticles that seaweed generates in enhancing protein nutrition and production systems, though irresistible, must be professionally considered on the backdrop of safety, toxicity, and regulatory oversight. It is these properties that make nanoparticles so functionally versatile like small size, high reactivity, and crossing biological barriers, which, on the other hand, raise certain well-founded concerns regarding potential interactions between nanoparticles and the environment and the living beings (Cotas et al., 2024). In this way, before the mainstream use of such new materials on the food chain, a serious and clear assessment of the risk profile of such materials is a scientific and ethical necessity. This is initiated by basic research into their biocompatibility and digestibility (Pathak et al., 2025). In the case of nanoparticles that are to enter the food or feces, the most important point of interaction is in the gastrointestinal tract. It is important to know how the acidic environment of the stomach and the enzymatic and microbial environment of the intestines, which are complex and variable conditions of the gut, interact with the nanoparticles, and vice versa. An important reason is the capping layer of seaweed, which is more likely to be identified and acted upon by the digestive enzymes and intestinal microbiota than a polymer made of synthetic material (Bouwmeester et al., 2018). This will affect the rate of dissolution of the nanoparticle, the possible release of the metal ions, and the overall digestibility of the nanoparticle. The probable consequence of this is a decline of the nanoparticles into harmless components that can be metabolized or eliminated in the body.

This preliminary understanding should be complemented by systematic and tiered toxicological evaluations in order to develop a strong safety case. In vitro studies usually use cell cultures to screen for both acute cytotoxicity, oxidative stress, and inflammatory reactions. This type of controlled experiment provides scientists with the opportunity to investigate the working of cells at the most basic level and define dose-response associations to determine possible risks, then proceed to more complicated whole-organism experiments (Awashra & Młynarz, 2023). Yet, safety testing in the gold standard is still in the in vivo tests, which involve the investigation of the impact of exposing nanoparticles to living model organisms, which in most cases are rodents. These investigations are essential to understand the effects of the nanoparticles on the body system, such as biodistribution, tracking the pathways of the nanoparticles within the body once ingested, chronic toxicity, reproductive health effects, and even carcinogenicity. The distinct advantage of using seaweed-synthesized nanoparticles in the given models is the possibility that a natural capping of the particles could result in a more positive toxicology profile than the chemically synthesized nanoparticles. Indicatively, a zinc oxide nanoparticle capped with algal polysaccharides may be dissolved at a new rate in the gut lumen and generate a more controlled zinc ion release, preventing the sharp acute cytotoxic responses that may take place with pure or more synthetically-stabilized nanoparticles (Hazeem, 2022). This is a complete biological test that serves as the basis of information on which any further implementation will be evaluated.

In addition to the immediate impact on human and animal health, a full safety assessment should consider the overall environmental impact of the introduction of these nanomaterials into agricultural and food systems. The lifecycle of a nanoparticle does not cease at the point of consumption, but, in fact, it starts with the growth of the seaweed, then proceeds to the synthesizing process, usage, and finally recycling or disposal into the surroundings (Tolisano & Del Buono, 2023). The lifecycle is hence required to be carried out comprehensively in order to be able to measure the total environmental footprint, which includes elements like energy use, water use, as well as greenhouse gas emissions related to production, and compare it to the traditional methods it seeks to substitute. This discussion will find out whether the proposed nanotechnology has a true net good in terms of sustainability. Also, there is a need to evaluate the risk of environmental exposure. Nanofertilizer or nanoaquaculture feed nanoparticles will always find their way into the soil and water systems (Stojanova et al., 2025). They have a critical effect on the soil health, microbial communities, aquatic life, and useful insects, which are critical research topics. The important questions to be queried are whether these particles remain in the environment, transform, or accumulate in the food chain. The capping layer is organic, which potentially facilitates biodegradation, which is a great opportunity compared to the durable synthetic nanoparticles. On the other hand, the possibility of the metal core being emitted and affecting the sensitive soil bacteria or aquatic life should be investigated in detail so that the solution to sustainable protein production does not become a new issue for the environment.

The balancing between technological promise and possible danger is a rather complicated issue that remains under the jurisdiction of an ever-changing international regulatory environment. Presently, the authoritarian process of approving nanoparticles as food and food additives is hectic and multistage (He & Hwang, 2016). The United States has a system of regulation of these materials by the Food and Drug Administration (FDA), which covers food additives, generally recognized as safe (GRAS) substances, and novel food ingredients. The manufacturer to be approved has to submit exhaustive information that reflects the safety of the substance to be used, and now, in the case of nanomaterials, we have to include the specific characterization and the toxicological studies already mentioned. The FDA reiterates that the nanoscale version of a substance that has been approved in a bulk version cannot be assumed to be safe, but it is a new item that needs to be evaluated (Chávez-Hernández et al., 2024). Likewise, the European food and feed risk assessment of engineered nanomaterials has the European Food Safety Authority (EFSA), which has developed a robust guidance document. EFSA needs to be characterized physicochemically in detail, including its fortune and behavior in all biological systems, and toxicological information, including in vitro and in vivo studies. The regulatory approach is basically precautionary, whereby the burden of proof lies with the applicant to prove safety (Rasmussen et al., 2025).

The existing regulatory system poses major challenges to the commercialization of nanoparticles made of seaweed. The cost of producing the necessary safety information is expected to be high because of the natural complexity and variability of biologically synthesized nanomaterials, making the innovation process challenging. The differences between the different assortments of seaweed extracts (by species, season, or geography) could lead to slight changes in the consequential nanoparticles, and this could question uniformity as well as the reproducibility of the safety data with each batch of seaweed extract (Zhang et al., 2020). This indicates the significance of high accuracy and standardization of the synthesis and purification processes as discussed in the earlier chapters. However, despite all these other issues, the green-synthesized nanoparticles have their own advantages in regulation. As long as the constituent elements, such as the seaweed extract and the metal salt, have already been approved in the food industry and the production procedure can be shown to produce a substance capable of being digested and broken down to safe and well-recognized elements, a solid argument can be made on safety. They should embark on a collective move that brings together scientists, industry, and regulators to develop standardized processes for undertaking safety tests of green nanomaterials.

9. Challenges, future perspectives, and conclusion

The mission of the science and application of seaweed-based nanoparticles is evidence of a potentially diverse and promising field, at the interface of green chemistry, nutrition science, and the science of sustainable agronomics. However, the pathway between the promising laboratory results and the large-scale practical application is not that easy. The technical challenge of transferring the gram-scale production in a controlled laboratory setting into a kilogram or ton-scale production required in an industrial setting is a major challenge. The advantage of the green synthesis technique is that it requires the utilization of the variable and complex chemical composition of the biological extracts, which is difficult to scale up (Hanna et al., 2025). In order to find some consistency within the batches, in which the source of the seaweed could vary by season and location, as well as species, a degree of standardization and quality control is required, which is one of the main issues of process engineering currently. The homogeneity of temperature and the dynamics of mixing that can easily be manipulated in a small beaker have become complex in large reaction vessels. Besides, downstream processing, including purification, concentration, and drying of the nanoparticles into a stable, storage-formable powder, without leading to aggregation, will require the development of new cost-effective, energy-efficient unit operations. The mission of such scale-up difficulties is a crucial precondition of the economic feasibility of this technology, because a stable and consistent production is the basis on which any business firms should be organized.

The issue of economic feasibility is closely connected with these technical obstacles and leads to a wider consideration of the market environment. The manufacturing price of the seaweed-synthesized nanoparticles has to be competitive and provide a distinct value over current competitors that involves both standard chemically manufactured nanoparticle formulations and traditional food additives and farm inputs. The techno-economic analysis is required in detail to determine the amount of costs involved in cultivating seaweed or sustainable harvesting, extracting, creating nanoparticles, and purifying. The raw materials might be cheap and renewable, but the energy and infrastructure expenses of the process may be prohibitive unless optimized. The market potential is, however, vast and expanding. The increasing consumer preference for clean-label, natural, and sustainable products presents a good opportunity to adopt green nanotechnology. In high-value niches like nutraceuticals, targeted delivery of nutrients, and precision farming, the better performance of these advanced materials might be worth paying more (Magnabosco et al., 2023).

In addition to the technical and economic obstacles that exist in the present, the consistent positive development of this field depends on the provision of the most significant knowledge gaps by conducting specific research in the future. The safety tests mentioned above, though necessary, are usually short-term tests. The most important research direction should be to start explaining the impact of chronic exposure to these nanoparticles in both humans and animals by first undertaking long-term low-dose studies. In the same way, longitudinal ecological analyses are needed to observe the destiny and the survival of these materials within complicated ecosystems and to trace the path of these materials in the soil, water, and food webs across seasons and years. This information is critical to the confirmation of the environmental safety arguments of green synthesis and evidence-based regulation policies. At the same time, the scope of functions of this technology is broadening into the sphere of accuracy and intelligence. The future of nanoparticle studies will see more investigations into the development of so-called smart nanoparticles, which can be used as targeted delivery systems releasing their nutritional or therapeutic load in response to environmental stimuli. Such a notion of smart targeting is the future of nutritional personalization (Kulkarni et al., 2023).

The use of this smartness continues brilliantly in the field of food packaging, where nanoparticles produced by seaweed, which possess antimicrobial and antioxidant properties, can be incorporated into the biopolymer films to form active smart packaging. Suppose a bottle coating of protein-rich foods that not only breaks down without any harm but also checks and reacts as a consequence of spoilage. A material of this kind would be colored when there are pathogens or metabolic by-products, with the inclusion of nanosensors. This would provide a visual depiction of the freshness and safety of the food to the consumer (Yao et al., 2024). The direct advantage is that this has enhanced food security by reducing the post-harvest losses and enhancing the quality of food sources of protein. The future research agenda is, therefore, two-fold that it must not only fill the gaps in the knowledge on the topic of safety in the long term rigorously, but also overcome the boundaries of innovation and develop more advanced, responsive, and efficient nano-systems of the entire food production chain. It will also be interdisciplinary in bringing together marine biologists, nanotechnologists, food scientists, toxicologists, and engineers in the same mission of ensuring perfection and accountability when using this powerful technology.

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