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CLEANER PRODUCTION AND SUSTAINABLE PROCESSES FOR ENVIRONMENTAL REMEDIATION

Eco-friendly and safe alternatives for the valorization of shrimp farming waste

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Abstract
The seafood industry generates waste, including shells, bones, intestines, and wastewater. The discards are nutrient-rich, containing varying concentrations of carotenoids, proteins, chitin, and other minerals. Thus, it is imperative to subject seafood waste, including shrimp waste (SW), to secondary processing and valorization for demineralization and deproteination to retrieve industrially essential compounds. Although several chemical processes are available for SW processing, most of them are inherently ecotoxic. Bioconversion of SW is cost-effective, ecofriendly, and safe. Microbial fermentation and the action of exogenous enzymes are among the significant SW bioconversion processes that transform seafood waste into valuable products. SW is a potential raw material for agrochemicals, microbial culture media, adsorbents, therapeutics, nutraceuticals, and bio-nanomaterials. This review comprehensively elucidates the valorization approaches of SW, addressing the drawbacks of chemically mediated methods for SW treatments. It is a broad overview of the applications associated with nutrient-rich SW, besides highlighting the role of major shrimp-producing countries in exploring SW to achieve safe, ecofriendly, and efficient bio-products.

Keywords Seafood waste · Applications · Chitin · Chitosan · Agrochemicals · Nanomaterials

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Introduction

Seafoods are integral to sustainability and food security, supporting economic development and human health (Stetkiewicz et al. 2022). In 2018, global seafood production was reportedly 178.5 million tons (MTs) (Saleh et al. 2022). The seafood demand is expected to increase by 60%, and it is projected to reach 9.8 billion by 2050 (Costello et al. 2020). The marine ecosystems provide seafoods from finfish (tuna, herring, pollock, whiting, and mackerel) and crustaceans (prawn, shrimp, crab, mollusks, and lobster) (Mahaffey 2004; Hosomi et al. 2012; Liu and Ralston 2021). There are hundreds of shrimp species found worldwide, but only 20 are commercially significant like *Litopenaeus vannamei* (white leg shrimp), *Penaeus monodon* (giant tiger prawn) (Van Quyen et al. 2020; Nisar et al. 2021; García-Ballesteros et al. 2021), and *Acetes japonicus* (Akiami paste shrimp) (Aziz et al. 2010). About 40% of the shrimp is discarded as waste which includes head and body carapace mostly (Miget 1991; Chen et al. 2022; AlFaris et al. 2022). Some of the SW is used as food and feed in animals and aquaculture (Nargis et al. 2006; Mansyur et al. 2021; Liu et al. 2021b), but most of it remains unutilized and is disposed of openly in landfills (Ravanipour et al. 2021), incinerated, or thrown in the oceans (Mao et al. 2017; Yadav et al. 2019). The SW disposal sites are potential hotspots of obnoxious odor and production of fumes, gases, and dust (Páez-Osuna et al. 1998; Srisertpol et al. 2013; Susetyaningsih et al. 2020). The fast degradation of the SW can lead to the emergence and transmission of pathogens through rodents, mosquitoes, and flies, which puts human lives at risk (Calzolari 2016; Dauda et al. 2019; El Amri et al. 2020).

Several chemical and bio-based methods retrieve valuable compounds from nutrient-rich SW (Ambigaipalan and Shahidi 2017). The SW is rich in nutrients like proteins (Mizani et al. 2005), chitin (Zhao et al. 2019), lipids (Ahmadkelayeh and Hawboldt 2020), and pigments (Moghadam Jafari et al. 2012), each with significant commercial value (Kandra et al. 2012). After cellulose, chitin is the most abundant biopolymer on earth. Besides shrimps, it is present in fungi and insect exoskeletons (Forsberg et al. 2014). Chitin is also highly crystalline, with the chains arranged in a repeating pattern that gives the material its strength and rigidity. The crystal structure of chitin is stabilized by hydrogen bonds between adjacent chains and by interactions between the acetyl groups and the adjacent sugar rings (Shahidi and Abuzaytoun 2005). Chitin is rich in nitrogen, thus having a wide range of applications in the pharmaceutical industry (Elieh-Ali-Komi and Hamblin 2016). Calcium carbonate also has a wide range of applications in agriculture (Minson 1990), pharmacy (Trushina et al. 2022), and paper (Schabel et al. 2014) industries. Other sources of calcium carbonate include limestone and marble (Gaber 2018). However, contaminants like heavy metals (Hunter et al. 2020) and microplastics (Karami et al. 2017) may cripple their direct human usage. Shell biorefinery is a concept that involves the conversion of shell waste, such as shrimp and crab shells, into value-added products through a series of biotechnological processes. The biorefinery approach aims to utilize all components of shell waste, including proteins, minerals, and chitin, to produce various products such as biofuels, biopolymers, and nutraceuticals. Shell biorefinery has the potential to be a sustainable and economically viable solution for managing shell waste, as well as reducing the reliance on fossil fuels and virgin materials (Chen et al. 2021b; Vicente et al. 2022). Furthermore, the development of shell biorefinery processes can provide opportunities for the creation of new industries and jobs, particularly in coastal communities with a high concentration of shell waste from the seafood industry. The synthesis of chalk from shells can be a good constituent of pills. The presence of proteins makes SW a good ingredient in animal and fish feed (Pattanaik et al. 2021).

The conventional extraction techniques used in processing the SW lead to the generation of abundant wastewater during demineralization and deproteination (Islam et al. 2004). This wastewater contains significant amounts of calcium and proteins (Bataille and Bataille 1983; Lee et al. 2017). Unfortunately, this wastewater mostly remains unutilized due to the higher concentration of sodium and chloride ions (Husnah 2017), high salinity (Djumanto et al. 2018), and corrosiveness (Anh et al. 2010). Scientists have tried several bioconversion processes using microorganisms as an alternative to potent alkali/alkali agents (Ghorbel-Bellaaj et al. 2012; Sedaghat et al. 2017; Subramanian et al. 2020; Abirami et al. 2021). The bioconversion process mediates the deproteination, demineralization, and fermentation processes (Zhao et al. 2019; Rasweefali et al. 2022). Biorefining and bioconversion are environmentally benign, safe, eco-friendly, and cost-effective (Leong et al. 2021). Other green technologies include methanogenesis (Ali et al. 2021b), and the use of oleaginous (oil-producing) microorganisms (Deng et al. 2020), to enhance and preserve the quality of extracted SW products. Due to their adaptability and abundance, microorganisms are fascinating SW bioconversion agents through fermentation (Bhaskar et al. 2007; Wani et al. 2022c). The fermentation is generally mediated by anaerobic, aerobic (Khorrami et al. 2015), facultative bacteria (Soleimani et al. 2017), mycelium (Teng et al. 2001), or microalgae (Nagappan et al. 2021). *Lactobacillus acidophilus*, *streptococcus thermophilus*, and *L. bulgaricus* are the most popular microorganism used in fermenting SW (Duan et al. 2011).

This review paper critically evaluates the current research on eco-friendly and safe alternatives for valorizing shrimp farming waste. The report will explore various methods of valorizing shrimp farming waste that are environmentally sustainable and safe for human and animal health. The review covers multiple topics, including extracting valuable compounds from SW, converting SW into energy, and using SW as a sustainable source of animal feed and fertilizer. The ultimate goal of this paper is to provide an overview of the most promising methods for valorizing shrimp farming waste and to identify areas for future research and development.

Shrimp farming and SW: a next-generation challenge

Shrimp cultivation is among the fastest-growing exercises in the world. About 10 MTs of crab, lobster, and SW is produced yearly. South Asia alone contributes to 2.5 MTs. Among the processed seafood, 45% comprises only shrimp (Yan and Chen 2015). The tremendous increase in shrimp production is a serious concern due to generating a large amount of SW. The generation of abundant waste threatens the environment due to its chemical nature and ease of degradation of seafood wastes (Hatje et al. 2016; Nirmal et al. 2020). About 75% of the production contribution comes from Asian countries, including China, Thailand, and Bangladesh, and 25% from Latin American countries like Mexico, Brazil, and Ecuador. Figure 1 gives an insight into the trends in shrimp production from 2000 to 2021 by significant producers (Martinez-Porchas and Martinez-Cordova 2012; Jayanthi et al. 2018; Chang et al. 2020b; Elwin et al. 2020; Salunke et al. 2020; Crona et al. 2020; Boyd et al. 2021; Van Nguyen et al. 2021; Yang et al. 2021; Davis et al. 2022). All types of shrimp farms have severe negative implications on the environment. During the early 1990s, 35% of mangrove forests vanished, and shrimp farming was the prime reason. In recent years, the shrimp culture has increased more significantly, thus negatively affecting the adjacent mangrove forests (Ahmed et al. 2018). Gao et al. (2022) reported that shrimp culturing affects the functional traits of mangrove plants. The long-term shrimp effluent may lead to disturbance in general fishery practices. The byproduct generated by shrimp ponds contains a considerable amount of organic matter resulting from leftover feed and metabolic waste of the shrimp. This byproduct has the capacity to contaminate not only the aquaculture environment but also the adjacent waters if used as a waste disposal site (Iber and Kasan 2021). Mangroves are effective in capturing the sediments and stabilizing the coastline, but the damage caused by extensive shrimp farming has led to a significant increase in erosion and floods (Ha et al. 2012; Tenório et al. 2015; Mechri et al. 2020; de Lacerda et al. 2021). The conversion of salt marshes to shrimp ponds influences the biogeochemical cycling in coastal wetlands. Gao et al. (2019) revealed that the presence of substrates in sediments affects the nitrate reduction processes and highlighted that shrimp culture might aggravate nitrogen loading in wetlands by increasing the production of ammonium. Regardless of the farming practice, the shrimp reservoirs are connected by a drain and supply canal (Primavera et al. 2007). Nearly 43 billion tons of shrimp wastewater reach coastal water in China (Biao and Kaijin 2007). The shrimp farmers generally use more feed for maximizing the shrimp growth and that feed is often in the form of pellets. Since shrimp nibble, up to 40% of the feed remains uneaten.

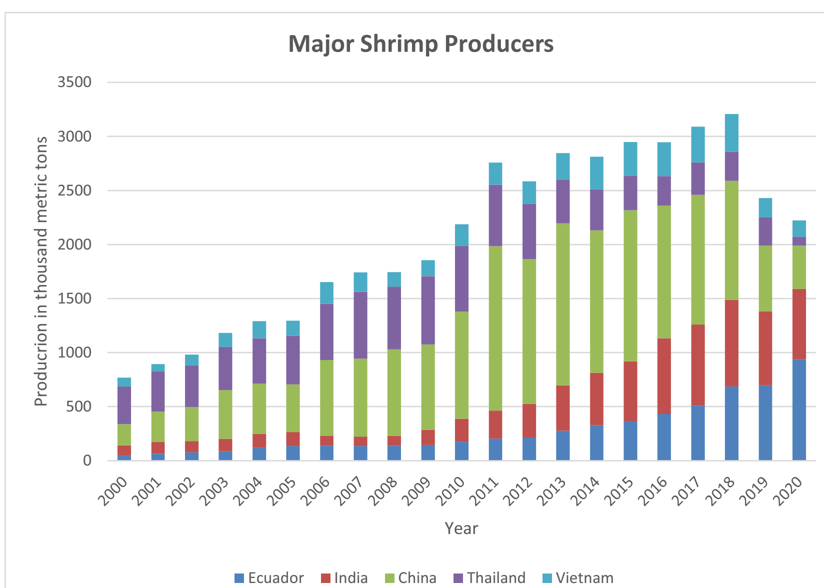

Fig. 1 Major shrimp-producing countries (2000–2020)

Shrimp feeds that are nutrient-rich effluents disintegrate very quickly causing economic loss to the farmer (Ayisi et al. 2017; AlFaris et al. 2022). The high accumulation of the feed in water bodies negatively impacts marine ecosystems because of the high phosphorus and nitrogen content in feeds that lead to eutrophication (Wu et al. 2002; Silvenius et al. 2017; Kong et al. 2020). These nutrients are essential for the photosynthesis of aquatic plants, and the optimum availability of these nutrients maintains their growth and metabolism. However, when excess nutrients from artificial sources such as shrimp farming enter the aquatic ecosystems, they lead to disproportionate algal and phytoplankton growth thus negatively affecting the environment (Lyu et al. 2021). The high phytoplankton density causes depletion of oxygen which is harmful to aquatic life and allows less light to reach the deeper parts of the water body causing plants to die (D'Angelo and Wiedenmann 2014). Fishes in hypoxic conditions experience a size reduction (Roman et al. 2019), egg malformation (Saha et al. 2022), respiratory problems (Domenici et al. 2017), and lethargy (Ackerly et al. 2018). Most of the disintegrated feed enters the environment causing serious ecological imbalance. Most of the feeding agents are anti-microbial; thus, the entry of antibiotics into the food chain increases the risk of antibiotic resistance which is among the leading global concerns (Thornber et al. 2020; Vaiyapuri et al. 2021). The inappropriate disposal of SW can provide a niche to rodents, flies, cockroaches, and mosquitoes capable of transmitting infections (Gwenzi et al. 2021).

Land subsidence due to increased salinity is a significant concern with shrimp farming in Vietnam. The red shrimp of Argentina is a popular shellfish. It yields about 18,000 MTs of waste annually, leading to ecological imbalance and environmental pollution in Argentine Patagonia (Cretton et al. 2021). To maintain the optimum salinity in the ponds, farmers pump a substantial amount of groundwater. Thus, seawater intrudes into the land, threatening the food supply (Boretti 2020). In the areas where intensive shrimp farming is carried out, the salinity exceeds the tolerance level during extreme conditions, creating problems for the biota. The trypsin and chymotrypsin mRNA downregulation at 2 practical salinity units (psu) and 10 psu has been reported in *L. vannamei* (Gao et al., 2016a,b). Besides, shrimp farmers generally use chemicals (formalin, sodium chloride, potassium permanganate, trifluralin), medications (florfenicol, enrofloxacin, sarafloxacin, oxytetracycline), and supplements (prebiotics, phytomolecules, and organic acids) for healthy shrimp farming (Luu et al. 2021). However, most of them reach public waterways making humans vulnerable to different ailments. Microplastics that threaten marine and human life have been reported in *P. monodon* and *Metapenaeus monoocerous* (brown shrimp). Thus, shrimp can act as a carrier for microplastics (Hossain et al. 2020; Nan et al. 2020), heavy metals (Baki et al. 2018), and microbial infectious agents (Chen et al. 2019; Wani et al. 2023b). The waste generation factor for shrimp and fish was estimated at 42% and 32.67%, respectively, accounting for 29,388 tons of waste per year in Bushehr province, Iran (Ravanipour et al. 2021). Global shrimp production rose by about 8% in 2021, and a growth of 5% is also expected for 2022 (Nguyen et al. 2021a; Yue and Shen 2022). Taking the harsh weather conditions of India into consideration, India was replaced by Ecuador as the world's top shrimp exporter by both value and volume recently (Patil et al. 2021). Brazil grew by about 23.8% in 2021 (Valenti et al. 2021), whereas Thailand grew by 12.8% (Boyd et al. 2022). However, shrimp is a valuable aquaculture member of crustaceans, processed for meat, leaving the head and carapace as waste. Shrimps are usually beheaded, and the exoskeleton is removed at the landing before sending to the processing industries (Mechri et al. 2020). Shrimp's protein and oil-rich heads mainly remain unutilized (Hannan et al. 2022; Saleh et al. 2022). Depending on the shrimp species, 40–45% of shrimp material by weight is left behind as waste. The discarded waste threatens the endangered species because of the high perishability of shrimp biomaterial (Zhang et al. 2018). The fast decay leads to enormous biogenic amine production with an offensive smell (Biji et al. 2016). Thus, it is imperative to look for appropriate strategies to prevent the early decay of the SW and convert the shrimp biomaterial into valuable products.

Strategies for SW utilization

Shrimp production has increased tremendously due to the adoption of intensive farming and the expansion of farming areas (Fig. 1) (Hatje et al. 2016; Patil et al. 2021). This has escalated the environmental impact of shrimp farming (Anh et al. 2010). Both farmers and researchers work for SW management, yet complete sludge management cannot be attained. Biodiversity loss, habitat destruction, disease outbreak, and water pollution resulting from the discharge of metabolites from shrimp culture are a matter of concern (Hatje et al. 2016). Shells harbor beneficial chemicals—calcium carbonate (20–50%) (Minson 1990), protein (20–40%) (Mizani et al. 2005), and chitin (15–40%) (Teng et al. 2001). The potential use of SW shells is largely ignored. Over the years, scientists have tried to work out sustainable ways to maximize the use of SW. The dried shrimp shells value only about $100 per ton (Ray et al. 2021). These shells can be processed and ground down for the extraction of several metabolites for use in animal feed (Evers and Carroll 1996), microbial growth media (Mathivanan et al. 2021), and bio-adsorbent (Doan et al. 2020). Several methods have been employed to extract valuable chemicals from SW (Sachindra and Mahendrakar 2005; Moghadam Jafari et al. 2012; Lee et al. 2017). The fractionation process separates different components (Bradić et al. 2020). The proteins are isolated by using sodium hydroxide, while calcium carbonate is decomposed using hydrochloric acid (Zhao et al. 2019). Both are hazardous and corrosive, thus impacting the environment negatively. Chitosan production from chitin also requires treatment with concentrated sodium hydroxide (Evans et al. 2011; Gomes et al. 2016). The chemical structure of chitosan is similar to that of chitin, with a linear chain of GlcN units linked together by beta-1,4 glycosidic bonds. However, unlike chitin, chitosan contains a higher percentage of free amino groups (-NH2) due to the deacetylation process. This gives chitosan a more positively charged character than chitin, making it soluble in acidic solutions and allowing it to form complexes with negatively charged molecules such as DNA, proteins, and polysaccharides (Muzzarelli and Muzzarelli 2005). The transformation of chitosan into other chemicals also poses several challenges (Hu and Gänzle 2019). Chitin is crystalline, preventing reagents from reacting with the other polymer chains. As a result, the chains undergo side reactions resulting in the formation of complex compounds (Rinaudo 2006). Thus, establishing sustainable ways for processing SW needs tremendous advancement in technology. The research groups from Mexico and the UK showed lactic acid fermentation for chitin production. They processed about 50 kg of shell waste in a single reactor (Cira et al. 2002; Beaney et al. 2005). A group of scientists in the USA and China developed a bacterial consortium capable of decomposing calcium carbonate and consuming proteins (Zhang et al. 2012; Liu et al. 2014a; Rahayu et al. 2022).

SW and valorization

Waste valorization includes recycling, reusing, and composting different waste materials and their conversion into valuable materials, fuels, chemicals, or other energy sources (Nazir et al. 2021). Seafood waste often produces obnoxious gases like ammonia and methane, which can be toxic to humans and other ecosystems. Valorization of seafood waste such as SW offers economic and environmental advantages by bioprospecting SW and reducing the problems that arise with conventional disposal methods (Mathew et al. 2020; Cadano et al. 2021). SW is subjected to drying, grinding, and sieving to improve valorization (Saini et al. 2020). The SW is sorted either dried or fresh for chitin extraction, depending on the nature of the valorized product. The chemical treatment of SW includes demineralization and deproteination. For demineralization, calcium carbonate in shells is removed using formic acid, HCl, acetic acid, or sulfuric acid (Percot et al. 2003; Al Shaqsi et al. 2020). Said Al Hoqani et al. (2020) optimized and isolated chitin and chitosan from Omani SW using chemicals like HCl, NaOH, and hydrogen peroxide (H_20_2). Tolesa et al. (2019) extracted chitin and chitosan from SW using ammonium-based ionic liquids with a higher degree of selectivity. However, using chemical solutions alters chitin's physiochemical properties, deacetylation, depolymerization, and release of acidic effluents (Sutarih et al. 2019).

Eco-friendly methods for a green economy can effectively valorize SW. Different methods are applied for deproteination and demineralization processes to replace hazardous chemicals like HCl and NaOH (Zhang et al. 2014; Feng et al. 2019; Bradić et al. 2020; Chandra Roy et al. 2021). Figure 2 gives an insight into the processing strategies used to recover valuable products from shrimp/SW. Huang et al. (2018a,b) used natural eutectic solvents to produce green and facile chitin from crustacean shells. The eutectic solvents are composed of natural metabolites that pose a danger to the environment. Zhao et al. (2019) separated chitin from SW using a two-step extraction strategy. Firstly, citric acid mediated the removal of shrimp shells with a demineralization efficiency of 98%, followed by the 88% deproteinization achieved by applying eutectic solvents with the help of a microwave. The calcium carbonate produced from the SW reacts with lactic acid synthesized by the bacteria, leading to calcium lactate formation. The derived calcium lactate is separated easily for various industrial applications. Chitin is obtained from wet and dried waste of *P. monodon* after deproteinizing with proteolytic enrichment cultures. Bioprocessing SW this way results in the production of highly pure chitin. The viscosity is higher than the commercially available chitin (Xu et al. 2013). Xie et al. (2021) also used an ecofriendly and efficient two-step fermentation step to extract chitin by LA-producing *L. acidophilus* and protease-producing *Exiguobacterium profundum*. To improve chitin extraction, atmospheric and room temperature plasma technology is used to induce mutations in *E. profundum*, a protease-producing bacteria (Xin et al. 2020). The deproteination of SW was initially carried out by proteolytic enzymes like rhozyme-62, trypsin, and cold trypsin. Duong and Nghia (2014) studied the kinetics and optimization of chitin extraction from SW using pepsin. Chymotrypsin, papain, alcalase, and savinase have been applied for protein and chitin extraction, besides other valuable by-products. Trypsin showed 55% recovery of carotenoid pigment from *Metapenaeus monoceros* in 4 h, while for the same period and same pigment 50% recovery was achieved using papain and pepsin (Chakrabarti 2002). De Holanda and Netto (2006) recovered chitin, protein, and astaxanthin from *Xiphopenaeus kroyeri* SW using pancreatin and alcalase.

SW Valorization by fermentation

Generally, two methods are adopted to utilize SW. One is to subject SW to an alkali-acid (hydrochloric acid-sodium hydroxide) solution sequentially to eliminate minerals, lipids,

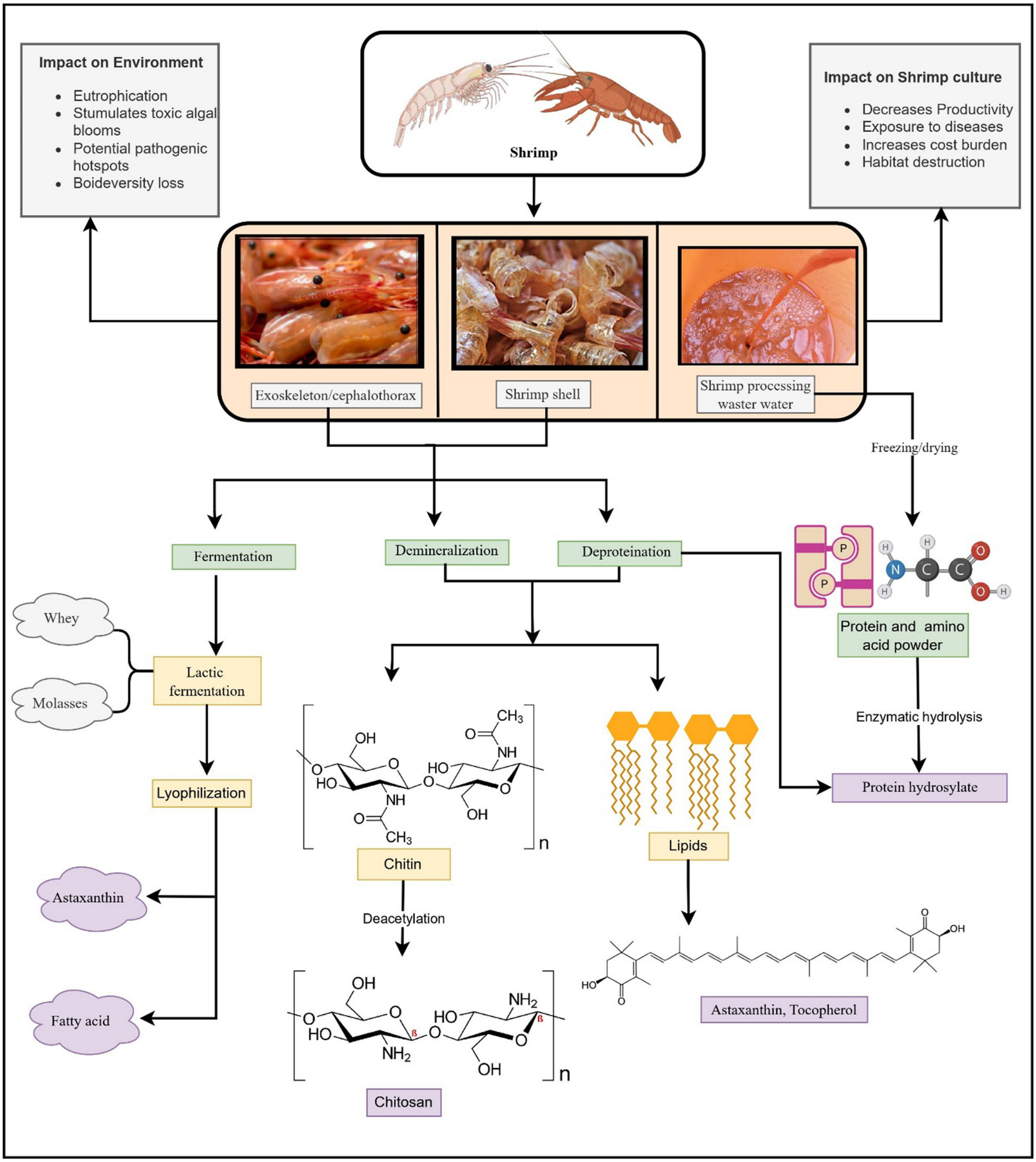

Fig. 2 Processing shrimp/shrimp waste by fermentation, deproteination, and demineralization to produce industrially important products

and proteins (Zhao et al. 2019). However, other than chitin, no other material can be extracted. Another strategy is to recover proteins by autolysis or to hydrolyze with exogenous proteinase (Cao et al. 2009; Nikoo et al. 2021). The protein hydrolysate produced this way results in the production of a bitter taste and fishy odor. Fermentation offers an advantage in overcoming these limitations by fermenting SW with lactic acid (LA) bacteria (Duan et al. 2011). This method ensures the recovery of chitin, proteins, and carotenoids without polluting the environment. Cira et al. (2002) studied LA fermentation of SW on a pilot scale with *Lactobacillus* spp. (Bhaskar et al. 2007; Sachindra et al. 2007; Choorit et al. 2008). They optimized the LA fermentation process for carotenoid and chitin recovery. Pacheco et al. (2009) studied the effect of temperature on astaxanthin and chitin recoveries from SW using *Lactiplantibaccillus plantarum*. Evers and Carroll (1996, 1998) studied the SW ensilage with *Enterococcus faecium* and *L. plantarum*. López-Cervantes et al. (2006) analyzed the free amino acids in SW. Shirai et al. (2001) studied the effect of inoculation glucose concentration level in SW ensilation using *Lactobacillus* sp. Various types of fermentation can be used for carotenoid and chitin production from shrimps, mainly lactic acid fermentation has been used (Table 1). Shrimp residue was stabilized with the use of tropical *Lactobacillus* bacterial culture. This mixed culture of *Lactobacillus* increases the yield of astaxanthins (Cira et al. 2002; Pacheco et al. 2009). Commercially, this antioxidant (astaxanthin) production is done by petroleum ether: acetone: water (15:75:10) to get a high yield and fast extraction (Hu et al. 2019). In some cases, enzymatic extraction comes into play, especially when protein-pigment complexes are needed (Wang et al. 2021). These complexes are reduced to get individual products, e.g., sayinase TM (Armenta-López et al. 2002). Lactic acid fermentation produced a considerable amount of astaxanthin and chitin. In a few studies, a column reactor was designed to get efficient chitin extraction, giving about 77% of the yield (No et al. 1989; Shahidi and Synowiecki 1991; Nguyen et al. 2021b). The protein in shrimps makes a complex with carotenoids and chitin. Hence, it is necessary to deproteinize SW. *Brevibacillus parabrevis* grown in liquid broth can deproteinize SW by producing chitin, calcium carbonate, and prebiotics (Doan et al. 2019). *Bacillus licheniformis*, *Lactobacillus* spp., and *Saccharomyces cerevisiae* hold great potential in prebiotic, astaxanthins, and proteases production (Lim et al. 2019). There is also abundant wastewater discharge from shrimp aquaculture carrying a lot of nutrients in significant concentrations, leading to eutrophication. Scientists are cultivating Cyanobacteria using wastewater for biomass production. It reduces the cost of wastewater treatment, besides helping to produce abundant biomass for applications like biofuel production, nutraceutical synthesis, and other applications (Balaji et al. 2013; Wani et al. 2021). Krasaesueb et al. (2019) utilized SW water to produce poly-beta-hydroxybutyrate by *Synechocystis* sp. in a photobioreactor.

Bioprospecting valorized SW for industrial applications

SW is excessively rich in bioactive compounds like amino acids (López-Cervantes et al. 2006), lipids (Nikoo et al. 2021), and carotenoids (Chakrabarti 2002). Each of them has a high nutritional value. About 30% of chitin and other materials like pigments, proteins, and minerals can be extracted from SW. Japan has dominated the chitin/chitosan production market for 30–40 years. The chitosan market globally was estimated to be around $476.6 million in 2016, and it is expected to reach $1088.0 million by the end of 2022 (Zhang et al. 2021b). The compound annual growth rate for chitosan will likely increase to 24.7% by 2027, exemplifying its prominence in the industry (Pandit et al. 2021). A substantial amount of SW and other seafood is valorized for bioprospecting. However, there is still a dire need to expand its scope by looking for the best strategies to use this environment-friendly nutrient-rich waste fully.

Table 1 Valorization of shrimp waste (SW) through microbial fermentation for the production of chitin, chitosan, and industrially valuable products

Microorganisms	Shrimp/SW	Temperature and duration	Product	Reference
Acetobacter pasteurianus and *B. subtilis*	General SW	35 °C for 4 days	Chitin	Zhang et al. (2021a)
Alcaligens faecalis and *B. coagulans*	*L. vannamei*	25–45 °C for 12–48 h	Chitin	Rakshit et al. (2021)
B. pumilus	*Metapeneaus monoceros*	35 °C for 6 days	Chitin	Ghorbel-Bellaaj et al. (2013)
Brebibacillus parabrevis	Squid pens, shrimp shells, and crab shells	40 °C for 4 days	Chitin processing and production of probiotics	Doan et al. (2019)
L. rhamnoides and *B. amyloliquefaciens*	*L. vannamei*	37 °C for 48 h	Acetic acid, lactic acid, and propionic acid	Liu et al. (2020)
L. plantarum	*Xiphopenaeus Kroyeri*	35 °C for 5 days	Chitin and chitosan	Tanganini et al. (2020)
Micromonospora chaiyaphumensis	General SW	45° C for 3h	Chitin and protease	Mhamdi et al. (2017)
Pseudomonas aeruginosa	*Panaeus merguiensis*	30 °C for 4–6 days	Chitin and chitosan	Sedaghat et al. (2017)
Serratia marcescens	Marine chitinous wastes	27.5 °C for 8h	Prodigiosin	Nguyen et al. (2021b)
S. marcescens and *L. plantarum*	*L. Vannamei*	30 °C for 4 days	Chitin	Zhang et al. (2012)

Chitin hydrolysis

Hydrolysis of chitin is a process that involves the breakdown of chitin into its constituent monomers, N-acetylglucosamine (GlcNAc) (Chen et al. 2010). There are several methods of chitin hydrolysis, including chemical, physical, and biological methods. Chemical hydrolysis involves using strong acids or bases to break down chitin. Acid hydrolysis is the most commonly used method, consisting of hydrochloric acid, sulfuric acid, or phosphoric acid. Base hydrolysis involves using sodium hydroxide or potassium hydroxide (Rupley 1964). The hydrolysis reaction is carried out under high temperature and pressure, and the resulting GlcNAc monomers are purified by precipitation and filtration (Einbu and Vårum 2008). Physical hydrolysis involves the use of mechanical methods to break down chitin. High-pressure homogenization (Salaberria et al. 2015), ultrasonication (Villa-Lerma et al. 2013), and milling (Tran et al. 2019) are some of the physical methods used for chitin hydrolysis. Physical hydrolysis is less energy-intensive than chemical hydrolysis, a more environmentally friendly method (Sampath et al. 2022).

Biological hydrolysis involves the use of enzymes to break down chitin. Chitinases and chitosanases are the enzymes used for chitin hydrolysis (Kaczmarek et al. 2019; Chen et al. 2021a). Chitinases are enzymes that break down chitin into smaller oligomers, while chitosanases break down chitosan into GlcNAc monomers (Arnold et al. 2020; Ma et al. 2020). The enzymatic method of chitin hydrolysis involves using chitinase enzymes to break down chitin into its constituent monomers. Chitinases catalyze the hydrolysis of the β(1→4) glycosidic bonds in chitin (Beier and Bertilsson 2013). Chitinases are produced by a wide range of organisms, including bacteria, fungi, and insects (Poria et al. 2021). The enzymatic method of chitin hydrolysis has several advantages over other methods, such as chemical or physical methods. Enzymatic hydrolysis is selective, efficient, and environmentally friendly (Linhorst et al. 2021). The enzymatic method of chitin hydrolysis can be carried out using different types of chitinase enzymes, such as endochitinases (Wang et al. 2019), exochitinases (Raimundo et al. 2021), and lytic chitinases (Li et al. 2023). Endochitinases cleave the internal β(1→4) glycosidic bonds in chitin, whereas exochitinases cleave the terminal β(1→4) glycosidic bonds. Lytic chitinases are capable of breaking down chitin into small oligomers or monomers. The choice of chitinase enzyme depends on the desired degree of hydrolysis and the specific application of the hydrolyzed chitin (Kaczmarek et al. 2019). The enzymatic method of chitin hydrolysis can be carried out under different conditions, such as pH, temperature, substrate concentration, and enzyme concentration. The optimal conditions for chitin hydrolysis depend on the specific chitinase enzyme used and the type of chitin being hydrolyzed. The pH range for chitin hydrolysis is typically between 3 and 8, with an optimal pH of around 5 to 6 (Churklam and Aunpad 2020). The temperature range for chitin hydrolysis is usually between 30 and 60 °C, with an optimal temperature of around 50 to 55 °C. The enzymatic method of chitin hydrolysis has several applications in various industries (Zhao et al. 2010). Hydrolyzed chitin can be used as a fertilizer, animal feed, and food additive. Hydrolyzed chitin also has antimicrobial and antifungal properties, making it useful in the pharmaceutical and cosmetic industries (Casadidio et al. 2019). Hydrolyzed chitin can also be used to produce chitosan, which is a derivative of chitin that has different physical and chemical properties. Chitosan has applications in medicine, agriculture, and other industries (Park and Kim 2010; Elieh-Ali-Komi and Hamblin 2016).

SW as a sustainable alternative to agrochemicals

Agrochemicals such as fertilizers and pesticides have revolutionized modern agriculture by increasing crop yield, fighting pests and diseases, and improving crop varieties (Hillel 2008). However, these chemicals are one of the leading causes of soil, water, and air pollution (Akhtar and Mannan 2020; Pal et al. 2021). Furthermore, agrochemicals like fertilizers can contribute the climate change and global warming as they release greenhouse gases like nitrous oxide (Yadav et al. 2021). Hence, it is essential to look for alternatives to agrochemicals. Here, the bio-organic fertilizers obtained from natural sources like SW could be a cost-effective, environment-friendly, and sustainable option. Using SW extract enhanced the glucosinate content in broccoli and increased the yield compared to the broccoli plants that were unfertilized or fertilized with sheep manure (Øvsthus et al. 2015). Chitin, predominantly present in SW, is rich in nitrogen, phosphorus, calcium, and other vital nutrients necessary for plant growth (Fatima et al. 2018; Pal et al. 2021). Applying chitin obtained from SW as a biofertilizer improved the growth of potatoes and wheat compared to the plants treated with chemical fertilizer (Fatima et al. 2018).

Moreover, the yield of the wheat crop improved following the treatment of the plants with SW-derived chitin (Fatima et al. 2018). Chitosan obtained from the shell of *Portunus pelagicus* (blue swimming crab) has improved the micropropagation potential of *Dendrobium* orchids (Pornpienpakdee et al. 2010). Similarly, the chitin obtained by treating the mantis SW with alkaline protease assisted with microwave heating improved the photosynthesis, fresh weight, and isothiocyanate content in pak choi (Cui et al. 2022). However, obtaining the chitin from SW to be used as fertilizer can be hazardous to the environment due to the extensive use of strong acids and alkalis. An approach to overcome this limitation can be the fermentation of the SW by microbes producing protease and chitinase and applying the fermented hydrolysate as a biofertilizer (Pal et al. 2021). The fermented hydrolysate produced by the fermentation of shrimp shell powder by *Alcaligenis faecalis* SK10 has been used as a biofertilizer in *Cicer arietinum* and *Pisum sativum* (Pal et al. 2021). The treatment of these plants with fermented hydrolysate increased their stem height, root length, and chlorophyll content. The SW fermented hydrolysate-treated *C. arietinum* and *P. sativum* plants grew better than the plants treated with chitin and chitosan. Furthermore, the fermented hydrolysate improved the physio-chemical quality of the soil and invigorate the growth of phosphate solubilizing and nitrogen-fixing bacteria in the plant rhizosphere (Pal et al. 2021). Interestingly, the supernatant obtained by growing *Bacillus cereus* QQ308 in a liquid media containing shrimp cell powder (2%) has also been reported to enhance the growth of Chinese cabbage compared to the control plants (Chang et al. 2007).

SW-derived products can also be a potential source of antifungal agents against plant pathogenic fungi. The nitric acid extract of the *Parapenaeus longirostris* SW inhibited the growth of various phytopathogenic fungi and oomycetes such as *Penicillium commune*, *Penicillium digitatum*, *Penicillium italicum*, *Penicillium expansum*, *Fusarium sacchari*, *Fusarium proliferatum*, *Colletotrichum karsti*, *Colletotrichum acutatum*, *Colletotrichum acutatum gloeosporioides*, *Alternaria alternata*, *Alternaria arborescens*, *Phytophthora nicotianae*, and *Phytophthora citrophthora* under in vitro conditions (El boumlasy et al. 2021). Furthermore, the in vivo studies showed that the extract significantly reduced the rot severity in apples, oranges, and lemons caused by *P. digitatum* and *P. expansum* in comparison with the control (El boumlasy et al. 2021). Hydrolytic enzymes like chitinase and proteases can damage the cell wall of phytopathogenic fungi (Chang et al. 2007). The growth of various bacteria on chitin-rich SW can elicit the production of these hydrolytic enzymes (Wang et al. 2002b, a; Jellouli et al. 2008). The supernatant obtained by growing *Bacillus cereus* QQ308 in a liquid media containing shrimp cell powder (2%) inhibited the growth, germ tube elongation, and spore germination of phytopathogenic fungi like *Pythium ultimum*, *Fusarium solani*, and *Fusarium oxysporum* (Chang et al. 2007). Furthermore, the bioactive compound chitosan obtained from the SW has also been reported to have antifungal properties against plant pathogenic fungi such as *Phomopsis asparagi*, *A. alternata*, *Aspergillus niger*, *Rhizopus stolonifer*, and *Rhizopus oryzae* (Ing et al. 2012). Chitosan can inhibit fungal growth by damaging the fungal plasma membrane, inhibiting the mRNA synthesis, and hindering the availability of trace elements necessary for fungal growth by acting as chelating agents (Ing et al. 2012).

SW as a medium for the cultivation of microbes

Microorganisms are found everywhere. However, only 1–3% of the total microbiota have been explored due to difficulties in culturing the microorganisms in laboratory conditions. Even though metagenomics has enabled the exploration of several previously unknown microorganisms and their enzymes, there is still a need for alternative culturable strategies (Handelsman et al. 1998; Handelsman 2004; Wani et al. 2022d,a). The SW can act as a potential source of carbon and nitrogen for the growth of various microorganisms. Furthermore, the SW is rich in trace elements and amino acids (Mao et al. 2017). Thus, SW could be a cost-effective alternative to expensive microbial culture media commercially available. Since microbes are highly adaptable to nature, SW has been used as a medium for cultivating marine bacteria (Mathivanan et al. 2021). The 1% SW agar media with 50% aged seawater could grow marine bacteria from marine soil samples (Mathivanan et al. 2021). The overall cost of making the SW agar media was 1.8 and 3.6 times cheaper than nutrient agar and Zobell marine agar media, respectively (Mathivanan et al. 2021). SW has also been used to grow various bacteria and fungi to produce a plethora of enzymes (Wang et al. 1995; Rattanakit et al. 2002; Nguyen et al. 2021c). Primarily, SW has been used as a substrate for the increased production of enzymes like chitinase, protease, and chitosanase by different bacteria (Rattanakit et al. 2002; Wang et al. 2008; Jellouli et al. 2008). Proteases produced by microbes using SW can be used in detergents, food processing, silk degumming, and the leather industry (Razzaq et al. 2019).

Similarly, the chitinase produced using SW can be used as biopesticides, antifungal agents, waste management, and the production of single-cell proteins (Rathore and Gupta 2015; Singh et al. 2021). The microbes that were able to grow on SW and produce commercially important enzymes are listed in Table 2. The SW has also been used as a nitrogen and carbon source by *Serratia marcescens* to produce antimicrobial pigment prodigiosin (Nguyen et al., 2021b).

SW-induced stress management in plants

SW can be composted and used as a soil amendment, as it is rich in organic matter and nutrients such as nitrogen, phosphorus, and calcium. Incorporating SW into the soil can improve soil fertility, structure, and water-holding capacity, leading to better plant growth and yield (Ben Mbarek et al. 2019). SW can be used as a nutrient source in hydroponic culture to grow plants without soil (Ezziddine et al. 2021). SW can provide essential nutrients such as nitrogen, phosphorus, and potassium and micronutrients such as calcium and magnesium for

Table 2 The utilization of SW for the production of enzymes by various microorganisms

Microbe	Enzyme produced	Reference
Aspergillus sp. S 1–13	Chitinase	Rattanakit et al. (2002)
B. amyloliquefaciens V656	Chitinase	Wang et al. (2002b)
B. cereus TKU022	Chitosanase and protease	Liang et al. (2012)
Bacillus sp. APCMST-RS3	Protease	Maruthiah et al. (2015)
B. halodurans CAS6	Protease	Annamalai et al. (2013)
B. subtilis W-118	Chitinase	Wang et al. (2006)
Colletotrichum lindemuthianum	Chitin deacetylase, β-N-acetylhexosaminidase and endo-chitinase	Suresh et al. (2011)
Monascus purpureus CCRC31499	Chitinase	Wang et al. (2002a)
Paenibacillus mucilaginosus	Protease	Doan et al. (2020)
P. aeruginosa	Elastase	Jellouli et al. (2008)
P. aeruginosa A2	Protease	Ghorbel-Bellaaj et al. (2011)
P. aeruginosa K-187	Chitinase	Wang et al. (1995)
Pseudomonas sp. TKU015	Chitinase and chitosanase	Wang et al. (2008)
Serratia sp. TKU017	Chitinase and protease	Wang et al. (2010)

plant growth (Yang and Kim 2020). SW can be vermicomposted using worms. Vermicomposting can convert SW into nutrient-rich vermicompost, which can be used as a soil amendment or fertilizer for plant growth (Zheljazkov et al. 2011). Chitin and chitosan are complex polysaccharides found in the cell walls of fungi and exoskeletons of arthropods. They have been shown to play a role in plant stress resistance by inducing various defense mechanisms. Chitosan, a deacetylated form of chitin, causes systemic acquired resistance (SAR) in plants (Heil and Bostock 2002). SAR is a defense mechanism that protects plants from pathogens by triggering a systemic response throughout the plant. Chitosan has been shown to activate the production of various plant hormones, such as salicylic acid and jasmonic acid, which are involved in SAR (Métraux 2013). Chitosan also plays a role in improving plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity (Hassan et al. 2021; Sadak and Talaat 2021). Studies have shown that chitosan treatment can increase water uptake and retention in plant roots, improving drought tolerance (Ali et al. 2021a). Chitosan can also help plants to detoxify heavy metals by binding to them and preventing their uptake into plant tissues (Abdellatef et al. 2022). Chitin and chitosan have been shown to improve plant growth by promoting root development, increasing nutrient uptake, and enhancing photosynthesis. These effects can increase biomass and yield (Malerba and Cerana 2016; Xu et al. 2020). Chitin and chitosan have also been reported to improve plant growth by promoting root development, increasing nutrient uptake, and enhancing photosynthesis. These effects can increase biomass and yield (Ingle et al. 2022). Table 3 gives an insight into the potential applications of SW and its derivatives in plant systems.

Table 3 Applications of SW and its derivatives in plant systems

Plant	Shrimp waste/derivative	Mode of application	Effect	References
Trifolium repens	Chitosan	Endogenous	Drought resistance	Li et al. (2017)
Capsicum annuum	1% chitosan	Foliar application	*Phytophthora capsica* resistance	Esyanti et al. (2019)
Melissa officinalis	0.01 and 0.015% chitosan	Shoot spraying	Accumulation of defense enzymes	Fooladi Vanda et al. (2019)
Lactuca sativa	Chitosan-based microparticles	Foliar application	Improvement defense responses	Martin-Saldaña et al. (2018)
Triticum aestivum	Green chitosan NPs	Foliar application	Source of nano nitrogen	Saad et al. (2022)
Citrus reticulata	Chitin oligosaccharide	Leaf infiltration	Resistance against *Candidatus liberibacter*	Shi et al. (2019)
Pennisetum glaucum	Calcium-rich biochar	Tuber immersion	Improving antioxidant defense	Abo-Elyousr et al. (2022)
Nicotiana tabacum	Nanochitin whisker	Suspension culture	Resistance against fungal infections	Zhou et al. (2020)
Brassica oleracea and *Fragaria ananassa*	Chitin nanofibers	Foliar application	Resistance against *Alternaria brassicicola* and *Colletotrichum fructicola*	Parada et al. (2018)
Thymus daenensis	Chitosan	Foliar application	Resistance against drought stress	Emami Bistgani et al. (2017)

Bioremediation potential of SW and SW-derived products

SW and SW-derived products such as chitin and chitosan are used to remove harmful pollutants (Sánchez-Duarte et al. 2012; Dehghani et al. 2018; Akhbarizadeh et al. 2018; Kong et al. 2018; Yin et al. 2019). The mechanism involved in removing the pollutants by the SW is adsorption (Fabbricino et al. 2013). Furthermore, the mechanisms such as adsorption, surface complexation, electrostatic attraction, ion exchange, and chelation help chitosan and other products, such as biochar modified with SW, remove metals from aqueous solutions (Dima et al. 2015; Yin et al. 2019). Chitosan's high hydroxyl and amino content also aid in the adsorption of various heavy metals by forming complexes with amine groups (Omidinasab et al. 2018). In removing tetracycline from shrimp shell waste, the hydrogen bond between the hydroxyl groups of tetracycline and oxygen-containing groups of shrimp shell waste plays an essential role (Chang et al. 2020a). Hence, these waste products can act as bio-adsorbents to remove environmental pollutants (Jia et al. 2023). However, various parameters, most notably the pH of the solution, affect the adsorption of different pollutants by these bio-adsorbents (Akhbarizadeh et al. 2018; Pompeu et al. 2022). The adsorption mechanism and capacity/efficiency are also affected by the surface chemistry of the adsorbent material (Akhbarizadeh et al. 2018). The pH affects the adsorption sites, functionalities, and surface charge of adsorbents, eventually affecting the interaction between the adsorbent and the pollutants (Dotto et al. 2015; Yin et al. 2019). The existing form and the degree of ionization of contaminants are also affected by pH (Yin et al. 2019). It has been reported that the increasing pH, in the range of pH 4–8, increased the removal efficiency of manganese and barium, but the removal efficiency of vanadium, arsenic, and chromium decreased with increasing pH in the range of 4–8 by chitosan-activated montmorillonite obtained by processing shrimp shell (Akhbarizadeh et al. 2018). During the removal of methylene blue dye by ultrasonic surface-modified chitin obtained from *Penaeus brasiliensis* SW, the increasing pH (range 2–10) increased the dye removal percentage where maximum dye removal was obtained at pH 10 (Dotto et al. 2015). In the case of dye removal by chitin, the interactions between functional groups like hydroxyl and amino groups on the chitin surface and anionic groups on dyes play an essential role (Doan et al. 2020). Table 4 gives an overview of the bio-adsorbents derived from SW for the removal of different contaminants.

A study used chitosan derived from fermented SW to make chitosan-tripolyphosphate beads that adsorbed Alura red Monoazo food dye from an aqueous solution (Sánchez-Duarte et al. 2012). The chitosan-polyphosphate beads also efficiently removed the dye from highly acidic solutions (Sánchez-Duarte et al. 2012). Similarly, chitin and chitin nanowhiskers, obtained by processing SW, could remove crystal violet dye from wastewater. The chitin nanowhisker's potential to adsorb the crystal violet dye was better than chitin. The bigger pore size of the nanowhiskers than chitin and the rod shape of the nanowhiskers could have contributed to the higher dye removal ability of the chitin nanowhiskers (Druzian et al. 2019). Apart from dyes, SW-derived products have shown the potential to adsorb various heavy metals such as arsenic, chromium, copper, lead, zinc, iron, and nickel (Somerville and Norrström 2009; Mohanasrinivasan et al. 2014; Rech et al. 2019; Liu et al. 2021a).

Furthermore, the products obtained from processing the SW have been able to adsorb harmful radioactive elements such as uranium, vanadium, and palladium (Kong et al. 2018; Omidinasab et al. 2018). Their herbicide removal potential has also been studied (Yin et al. 2019). Table 4 provides information about various bio-adsorbents obtained from SW processing and their ability to adsorb various harmful pollutants.

SW in the production of animal feed

The solid SW constitutes 35% tissue protein, calcium carbonate, and chitin. The highly perishable SW can be a rich animal feed and silage ingredient if preserved adequately. Evers and Carroll (1996) performed multiple experiments to ferment shrimp and crab waste with molasses. They combined crab waste with 0, 5, 10, and 15% liquid molasses and stored it in mini-silos for 14 days. Fresh SW was combined with 0, 10, 15, 20, and 25% dry molasses and colony-forming bacteria for 6 days (Zakaria et al. 2022). They reported increased lactic acid fermentation with a significant decrease in ammonia, butyric, and propionic acid. *Penaeus* shrimp shells contain almost all essential amino acids, and their nutrient value is nearly equal to soybean meal (Liu et al. 2021b). However, most proteins are not retrieved from the SW because the current processing methodologies rapidly destroy them. As the demand for livestock feed increases, the transformation of SW into protein-rich animal feed needs more attention. Chitin and chitosan used in the food industry for crustacean canning and carotenoid recovery have proven economically feasible and environmentally friendly (Zhang et al. 2012). A considerable amount of astaxanthin was extracted during this extraction and modification process. This compound is mainly used as a fish feed component and for improving egg-laying quality (Abun and Haetami 2019). Chitosan has been tested as an ingredient for livestock animal feeds. No abnormality was reported in broilers and hens by feeding < 1.4 g of chitosan/kg of body weight/day for 239 days.

Table 4 Shrimp waste (SW)-derived bio-adsorbents for removal of harmful environmental pollutants

SW-derived bio-adsorbent	Pollutants	Sorption capacity/efficiency	Reference
Shell of Penaeus monodon (black tiger shrimp) and *L. vannamei* (white shrimp)	Arsenic	7.8×10^{-3} to 2.4×10^{-1} mg/g (white shrimp shell) and 8.1×10^{-3} to 5.0×10^{-1} mg/g (black tiger shrimp shell) in the pH range of 6.03–7.02	Chio et al. (2009)
Chitosan	Arsenic	1.3 mg/g at pH 4.41	Dehghani et al. (2018)
Ground shrimp shell	Chromium (III)	> 99% removal of chromium (III) from tannery wastewater	Fabbricino et al. (2013)
Chitosan and chitosan reticulated micro/nanoparticles obtained by processing Argentinian Patagonia shrimp (*Pleoticus muelleri*) shell	Chromium (VI)	38.8 mg/g for chitosan reticulated micro/nanoparticle and 66.9 mg/g for chitosan (at pH 4)	Dima et al. (2015)
Crushed shells of *Penaeus borealis* shrimp	Lead, cadmium, zinc, and copper	Lead (97%), cadmium (99%), zinc (99%), and copper (98%)	Somerville and Norrström (2009)
Chitosan-activated montmorillonite obtained by processing shrimp shell	Crude oil	87% at pH 7	Akhbarizadeh et al. (2018)
Ultrasonic surface-modified chitin obtained from *Penaeus brasiliensis* SW	Methylene blue	26.69 mg/g	Dotto et al. (2015)
Chitin obtained from shrimp head powder fermented by *Paenibacillus mucilaginosus*	Red number 7 dye and Congo red dye	99% (Congo red) and 97% (Red number 7)	Doan et al. (2020)
Chitosan obtained from shrimp shell waste	Copper, chromium, iron, and zinc present in leather industry effluent	98.97 (copper), 37.51 (chromium), 65.2 (iron), and 86.15 (zinc)	Mohanasrinivasan et al. (2014)
Metapenaeus ensis shrimp shell	Copper	0.72 mmol/g at pH 5	Liu et al. (2021a)
Acid-washed shrimp *Palinurus elephas* (Algerian shrimp) shells, chitin, and chitosan	Copper	16 mg/g (acid-washed SW), 24 mg/g (chitin), and 150 mg/g (chitosan) at pH 4	Maachou et al. (2019)
Unprocessed shrimp shell	Iron and chromium	63.4% (iron) and 62.2% (chromium) in the pH range of 6.3 to 7.45	Rech et al. (2019)
Trapa natans husk biochar modified with SW	Nickel and 2,4-dichlorphenol	863.24 mg/g for 2,4-dichlorophenol and 44.78 mg/g for nickel	Yin et al. (2019)
Raw shrimp shell waste	Tetracycline	229.98 mg/g at pH 7	Chang et al. (2020a)
Magnetic chitosan nanoparticles obtained by processing SW	Vanadium and palladium	192.3 mg/g (palladium) and 186.6 mg/g (vanadium)	Omidinasab et al. (2018)

The rate of digestion for both chitin and chitosan was reported to be 35–83% in rabbits and 88–98% in broilers and hens (Hirano et al. 1990). The major advantage associated with the use of SW shells in animal feed is that it enhances immunity (Pilotto et al. 2019). SW is known for the production of carotenoids like astaxanthin and beta-carotene, and they strongly inhibit lipid peroxidase formation, which improves yolk color and eggshell quality by exhibiting an antioxidant effect (Meng et al. 2010). The chitin-rich feed can help in improving milk production in cattle (Del Valle et al. 2017), production of good quality meat, and quality egg production in hens and ducks (Świątkiewicz et al. 2018). The properties like anti-microbial (Chang et al. 2007), antioxidant (Ngo and Kim 2014), and anti-cancer (Azuma et al. 2015) associated with SW-derived chitin make it an excellent biocompatible ingredient with usefulness in sustainable development. The consumption of chitin and chitosan helps in overcoming protein deficiency in animals besides helping bone forming and strengthening (Venkatesan et al. 2014; Kjalarsdóttir et al. 2019). These are also helpful in better gut health because they allow growing beneficial flora of microorganisms to flourish in the animal gut, reducing the risk of colon diseases in animals (Lopez-Santamarina et al. 2020).

Owing to its diverse nutritional value, looking for cost-effective processing strategies to retrieve maximum benefits from the SW is imperative. Both chemicals, as well as biological methods, have been employed to obtain the valuable components from SW. In chemical processes, the SW is subjected to alkali-acid treatment (Sachindra and Mahendrakar 2005; Zhang et al. 2014). In biological methods, the SW is subjected to a demineralization process by prebiotic bacteria (Abun and Haetami 2019). Chemical methods produce abundant yield, but the process is crippled by the side effects associated with the various chemical (Biao and Kaijin 2007). Due to their low metabolic activity, biological methods produce lower yields than chemical methods (El-Bialy and Abd El-Khalek 2020; Cabanillas-Bojórquez et al. 2021). One of the reasons for the poor standardization of chitin and chitosan is they are fundamental. In contrast, other natural polysaccharides (pectin, dextrin, cellulose, agar, and agarose) are acidic (Ali et al. 2020).

SW as a food packaging material

Constant efforts are made to promote using bio-composite materials for different purposes owing to their low cost, biodegradability, non-petroleum-based sources, and low carbon emissions (Mohanty et al. 2002). Chitosan offers many advantages in agriculture (de Oliveira et al. 2021), manufacturing, and pharmaceutical industries (Garg et al. 2019). The applicability of chitosan depends on the degree of chitin deacetylation. The deacetylation process controls the physiochemical parameter like the degradation rate. Using chitosan as an alternative to synthetic polymers in food packaging is of significant use due to its antimicrobial and biodegradable properties (Cazón and Vázquez 2019). Elhussieny et al. (2020) prepared chitosan composite films as polymeric matrices and found that the thermal degradation temperature of chitosan improves significantly with adding rice straw. The composite films degrade, leaving behind zero waste. Bio-based packaging films have been developed that contain liquefied shrimp shell chitin (Teixeira-Costa and Andrade 2021). The shelf-life of the cherry and tomatoes wrapped in these developed chitin-containing biofilms is extended by 10 days. The addition of beta-cyclodextrin enhances the antimicrobial potential of the bio-films, besides delaying the release of cinnamaldehyde (Qian et al. 2022). Al-Ali et al. (2021) investigated the properties of shrimp-extracted chitosan composite film combined with ginger essential oil. They reported that tensile strength decreases significantly with increased ginger essential oil concentration. However, an expansion also improves the elongation. The studies of Tamer et al. (2016) and Kumar et al. (2020) suggest that chitosan-based packaging films can be useful in pharmaceutical, cosmetic, and food industries because of their anti-free radical nature. Saridewi and Malik (2019) have developed bioplastic from *Manihot uttilisima* (cassava) peel and shrimp shells.

SW-derived compounds with anti-cancer potential

Like plant waste, SW is also rich in high-quality anti-cancer molecules. Some SW-derived compounds have been characterized by their anti-proliferative, pro-apoptotic, and anti-replicative action in different cancer cell lines (Abedian et al. 2019; Wani et al. 2022b, 2023a). The administration of astaxanthin inhibited tumor growth besides stimulating an immune response against tumor growth antigen. Astaxanthin treatment for prostate cancer cells for 9 days decreases tumor growth by 38% (Ranga Rao et al. 2010; Sun et al. 2020). Similar kinds of results were obtained by McCall et al. (2018) for breast cancer in vitro, Shin et al. (2022) in glioblastoma cell lines, and Kim et al. (2019) in colon cancer cells. The polyunsaturated fatty acid derivatives of shrimps have also been studied for their chemopreventive action in both in vitro and in vivo studies. Wilson-Sanchez et al. (2010) reported antiproliferative and anti-mutagenic activities of the compound present in the lipidic fraction of shrimp muscle. Chitosan suppresses the proliferation of MCF-7 breast cancer cell lines in a dose-dependent manner while being non-toxic to L929 fibroblast normal cells (Resmi et al. 2021).

SW-derived compounds with antimicrobial potential

Chitosan is antimicrobial against several microorganisms like yeast, filamentous fungi, and bacteria (Yilmaz Atay 2019). It has also shown antimycotic activity between 10 and 7750 mg/L concentrations depending on the type of microbial species (Shih et al. 2019; Confederat et al. 2021). Due to a lipopolysaccharide layer in gram-negative bacteria, chitosan shows more bacteriostatic and bactericidal effects again gram-positive bacteria (Raafat and Sahl 2009). Goy et al. (2016) evaluated the action of chitosan and its quaternized derivative on *Staphylococcus aureus* and *E. coli*. They reported a difference in the antimicrobial activity of chitosan with a more expressive movement of *S. aureus*, a gram-positive bacterium, while *E. coli*, a gram-negative bacterium, reported less sensitivity. Chitosan damages the microbial cell membrane by electrostatic interaction with phospholipids of negative charge. The membrane disruption is followed by its entry into the cell, which directly hampers nucleic acid and protein synthesis (Liu et al. 2004). Generally, bacterial growth in the bioethanol production industry is controlled by acid treatment and/or suitable antibiotics; both have severe environmental concerns (Kraemer et al. 2019; Américo-Pinheiro et al. 2021). So far, no study has reported using chitosan as a suitable alternative for controlling microbial contamination during fermentation. Studies have reported inhibitory effects of Chitosan on some the microorganisms like *Lactobacillus* sp. and *L. fermentum* (Jeon et al. 2001; Lee et al. 2002; Ristić et al. 2015). Rashidian et al. (2021) evaluated the antibacterial effect of the head of *L. vannamei* waste against pathogenic bacteria. They used fractionated hydrolysate generated by an alcalde and reported minimum inhibitory concentration in the 1–3 mg/L range against *Streptococcus iniae* and *Yersinia ruckeri*.

SW-derived compounds for the synthesis of nanomaterials

Using natural waste resources to synthesize nanomaterials is an eco-friendly approach to reusing and recycling waste materials for various applications. SW is a natural resource of biopolymers and minerals such as chitin, which serves as a raw material for the production of chitosan (Yadav et al. 2022). The use of chitin, chitosan, and their derivatives has been extensively used in the literature for the green synthesis of nanomaterials with a wide range of applications (Table 5) (Fig. 3). Chitosan nanoparticles (ChNPs) were synthesized for the first time by Ohya and coworkers in 1994 for intravenous administration of the anticancer medication 5-fluorouracil (Ohya et al. 1994). Since then, chitosan-based NPs have been used in a variety of fields, including agriculture (de Oliveira et al. 2021), food processing and preservation (Mesgari et al. 2021), drug delivery (Garg et al. 2019), and wastewater remediation (Olivera et al. 2016).

ChNPs have been employed in agriculture as pesticides (Campos et al. 2018), insecticides (Vallim et al. 2022), and herbicides (Grillo et al. 2014) to achieve high yield with better quality agricultural products (Zarei et al. 2015; Chouljenko et al. 2017; Choudhary et al. 2019; Bandara et al. 2020). Due to their cationic nature, non-toxicity, higher adsorption, and biodegradability properties, ChNPs may also be used as an encapsulating agent to produce slow-release fertilizers (Abdel-Aziz et al. 2016). Due to the abundance of hydroxyl and amino groups in the cross-linked structure of chitosan, its nanocomposites, NPs, and microstructures have been extensively exploited as an absorbent to remove different inorganic and organic contaminants such as phosphate, pesticides, dye, and heavy metal ions such as Cr(VI), Cr(III), Ni(II), Co(II), Cu(II), Cd(II), Hg(II), and Pb(II) (Cadogan et al. 2014; Fan et al. 2017; Divya and Jisha 2018; Zhang et al. 2019). Water treatment relies heavily on the cost-effective recycling of adsorbents, and magnetic ChNPs synthesized from Fe3O4 show tremendous promise for the cost-effective recycling of adsorbents under a magnetic field. To settle down pollutant particles during the flocculation stage in various water treatment procedures, chitosan-based NPs may also be used as bioflocculants (Lü et al. 2017; Lichtfouse et al. 2019).

ChNPs have been used in several pharmaceutical and biomedical applications, such as drug delivery wound treatment and enhancing the therapeutic effects of drugs (Annu et al. 2018). These applications of ChNPs are due to their physicochemical properties, such as enhanced absorption capability, mucoadhesive property, biodegradability, and biocompatibility. These nanomaterials have been extensively used in drug delivery, such as gene delivery (Li et al. 2015), vaccine delivery (Pawar and Jaganathan 2016; Marasini et al. 2016), per-oral delivery (Barbieri et al. 2015; Gao et al. 2016a), mucosal drug delivery (Martirosyan et al. 2014), buccal drug delivery (Mazzarino et al. 2014), nasal drug delivery (Shahnaz et al. 2012), ocular drug delivery (Zhang et al. 2016), vaginal drug delivery (Perinelli et al. 2018; Martínez-Pérez et al. 2018), pulmonary drug delivery (Jafarinejad et al. 2012), and cancer therapy (Lee et al. 2014; Nascimento et al. 2017; Sekar et al. 2018). ChNPs also exhibit antioxidant (Kumar et al. 2015), antifungal (Dananjaya et al. 2017), and antibacterial properties (Chandrasekaran et al. 2020). Recently, green synthesis of silver (Ag) NPs using Ch produced from bio-waste (prawn shell wastes) has been used as a tool for controlling lethal mosquitoes and various microbial pathogens, thereby addressing two significant public health concerns: waste recycling and mosquito vector control (Alshehri et al. 2020). Multiple studies have investigated the wound-healing potential of Ch-based NPs (Karri et al. 2016; Ehterami et al. 2018; Biranje et al. 2019; Fahimirad et al. 2021). The nanosized ChNPs allow for enhanced penetration through skin tissue and potentially into the wound region, resulting in more effective wound healing. Furthermore, the positive charge on polymeric ChNPs provides distinctive advantages. The strong positive charge of ChNPs allows them to interact with several negatively charged components, such as bacterial cells, mucosal surfaces, and cell surfaces (Loo et al. 2022).

Chitin, chitosan, and their derivatives obtained from SW offer a wide range of uses in nanotechnology. Their low toxicity, significant solubility, and versatility make them an ideal resource for nanotechnology. Therefore, efforts must be made to synthesize different nanomaterials from SW for beneficial use. These efforts provide an alternative for the remediation of SW in an eco-friendly manner and serve as a potential resource for synthesizing nontoxic and cost-effective nanomaterials for human use.

Table 5 Studies on the potential application of chitin- and chitosan-based nanomaterials

Application	Type of nanomaterial	Findings	References
Food and agriculture	ChNPs with high molecular weight (600 kDa)	Increased the chlorophyll content in coffee leaves by 30 to 50% and the photosynthetic rate by 30 to 60%. Increase the absorption of essential nutrients such as nitrogen, potassium, and magnesium—enhanced plant growth	Nguyen Van et al. (2013)
	ChNPs	Defense against rice blast fungus (*Pyricularia grisea*)	Manikandan and Sathiyabama (2016)
	ChNPs coating	Protection of fresh-cut apples by reducing microbial growth on	Pilon et al. (2015)
	ChNPs	Increased shelf-life and post-harvest protection of banana fruit	Lustriane et al. (2018)
	ChNPs-NPK fertilizer	Significant increase in growth, crop index, and harvest index of wheat plants significant increases	Abdel-Aziz et al. (2016)
	Carbon quantum dots in combination with Ch solution	Lower total bacterial count by inhibiting the growth of *Staphylococcus aureus*, *Escherichia coli*, and *Bacillus subtilis* in soy milk. Enhanced shelf life and improved stability of soy milk	Zhao et al. (2020)
Wastewater treatment and drinking water purification	Magnetic ChNPs	Targets Cd (II) and PB (II) in wastewater with an absorption capacity of 36.42 mg/g for Cd (II) and 79.24 mg/g for Pb (II)	Fan et al. (2017)
	Chitosan stabilized Fe/Cu NPs	Targets Cr (VI) with a removal efficiency of 90% in river water, 80% in smelting water, and 80% in tannery water	Jiang et al. (2018)
	Chitin nanocrystals	Removes up to 27% Ag(I) from water	Liu et al. (2014b)
	Chitosan-silver NPs	Removes 99.99% of bacteria from the drinking water within 15 min	Garcia Peña et al. (2017)
	Chitosan carbon nanotubes	Removes phosphate from wastewater with an absorption capacity of 36.1 mg/g and efficiency of 94–98%	Huang et al. (2018b)
Drug delivery	Chitosan/PVA NPs loaded with doxorubicin	Used to deliver anticancer drugs	Khdair et al. (2016)
	Chitosan nanospheres loaded by 5-fluorouracil	Chitosan particles were found to entrap 5-fluorouracil and deliver it to tumor cells	Cavalli et al. (2014)
	Chitosan-tripolyphosphate (TPP) NPs loaded with insulin	Lowering blood glucose levels by delivery of insulin for diabetes in rats	Pan et al. (2002)
	Curcumin-loaded chitosan-TPP NPs	Use for transdermal delivery	Nair et al. (2019)
	Chitin nano gel loaded with methotrexate	Deliver methotrexate more efficiently. Alternative to oral administration of methotrexate for psoriasis patients	Panonnummal et al. (2018)
Antimicrobial activity	ChNPs	Antimicrobial activity against *Alternaria alternate*, *Aspergillus niger*, *Botryosphaerica dothidea*, *Candida albicans*, *Escherichia coli*, *Fusarium solani*, *Klebsiella pneumoniae*, *Macrophomia phaseolina*, *N. oryzae*, *Nigrospora sphaerica*, *Rhizoctonia solani*, *S. typhimurium*, *Salmonella choleraesuis*, *Staphylococcus aureus*, and *Streptococcus pneumoniae*	Qi et al. (2004); Chávez de Paz et al. (2011); Nguyen et al. (2017); Divya et al. (2017); Divya and Jisha (2018)
	Ch-silver NPs	Antimicrobial activity against *Aspergillus flavus*, *Bacillus subtillus*, *Collectotrichum gloesporiodies*, *E. coli*, *P. aeruginosa*, *R. solani*, and *S. aureus*	Du et al. (2009); Honary et al. (2011); Ali et al. (2011); Namasivayam and Roy (2013); Chowdappa et al. (2014)

Table 5 (continued)

Application	Type of nanomaterial	Findings	References
Wound healing	ChNPs loaded with insulin	Wound dressings containing insulin-loaded CSNPs significantly reduced microbial penetration	Ehterami et al. (2018)
	ChNPs loaded with silver sulfadiazine	Antibacterial activity against gram-positive bacteria on wounds, antifungal activity reduction ranged from 20.35–36.85%	El-Feky et al. (2017)

Challenges in SW processing and utilization

The existing methods of SW valorization are expensive, destructive, and wasteful. SW is subjected to several rounds of chemical processes to obtain good quality products, which generate numerous ecotoxic byproducts besides increasing the cost of good quality chitin up to $200/kg. The effects of ecotoxicology of seafood waste processing include eutrophication, biotic depletion, habitat destruction, disease outbreaks, shortage of drinking water, siltation of corals, and water acidification. Besides abundant solid discards, the seafood processing industry generates voluminous amounts of wastewater by performing operations like washing, chilling, fileting, blanching, marination, and cooking. According to an estimate, 10–40 m^3 of water is required to process 1-ton waste (Arvanitoyannis and Kassaveti 2008). One of the European seafood processing factories releases about 1.500 m^3 of wastewater daily (Steinke and Barjenbruch 2010). Surimi production uses more water than canning, freezing, or curing (Park 2005).

The seafood processing industries face many operational challenges, such as price fluctuations, temperature control, sanitation, and tough regulations (Lan 2013). To achieve higher operational efficiency, substantial investment in applying advanced technology is needed to reduce wastage, maintain product quality, improve yield, and boost product shelf life. Bioconversion of seafood and SW, seen as a potential alternative to chemical-mediated treatment, has limitations that cripple its advanced applicability (Venugopal 2022). The processing rate is significantly slower than that of the chemically mediated processes. The obnoxious smell generated by the bioprocessing of SW is also problematic and needs immediate redressal. While applying microorganisms for the SW processing, there are higher chances of undesirable microbial growth leading to contamination which negatively affects the SW processing. The regulatory agencies have framed regulations to control the ecological impacts of seafood waste processing. The guidelines mainly propose the limits of wastewater discharge and facilities required for seafood processing. Shoushtarian and Negahban-Azar (2020) extensively reviewed the parameters promulgated by 70 regulatory agencies for human welfare and to prevent possible disease outbreaks like COVID-19.

Way forward

Establishing a sustainable and profitable industry from SW requires creative designs of green chemistry. The suitable fractionation to separate all the major SW components to avoid hazardous chemicals and minimize waste is imperative. Ball milling and steam explosion has been successfully applied for refining woody biomass, but it has largely been ignored in applying to seafood wastes, including shrimp shells. Solvent-free ball milling can effectively grind the surfaces for cell fractionation (Qu et al. 2017). Applying stream pressure with acid can liberate SW components (Jiao et al. 2015).

Further investigations are needed to discover new routes for converting chitin to other chemicals, enhancing yield, and easing product separation. Using ionic liquids can mediate the dissolving of carbohydrate polymers for chitin extraction. There is a dire need for all the major shrimp producers of the world to get together and establish new technology as the SW processing pipeline (Yang et al. 2019). The slow fermentation processes led by microorganisms can also be accelerated by engineering the genome of microorganisms. Over the years, genetic engineering has been used to alter microbial genomes, leading to the overproduction of valuable molecules. The metabolism is hijacked, providing sufficient energy to amplify the product formation. There is a need for the commercialization of seafood waste products to increase their economic value. Companies can collaborate with researchers to develop new value-added products, including nutraceuticals (Stephen et al. 2022), cosmetics, and bioplastics (Coppola et al. 2021), and market them to consumers. Implementing seafood waste management into a circular economy framework can create a more sustainable seafood industry. Circular economy models can help reduce waste and greenhouse gas emissions while promoting the recovery of valuable resources (Cooney et al. 2023). Collaboration among stakeholders, including seafood processors, researchers, and government agencies, is crucial for the sustainable management of seafood waste (Venugopal 2022). Partnerships can facilitate sharing of knowledge and expertise, promote innovation, and identify solutions to environmental and social challenges. Thus, substantial financial support from governments led by policymakers and researchers will help sustainably overcome the technical and ecological problems.

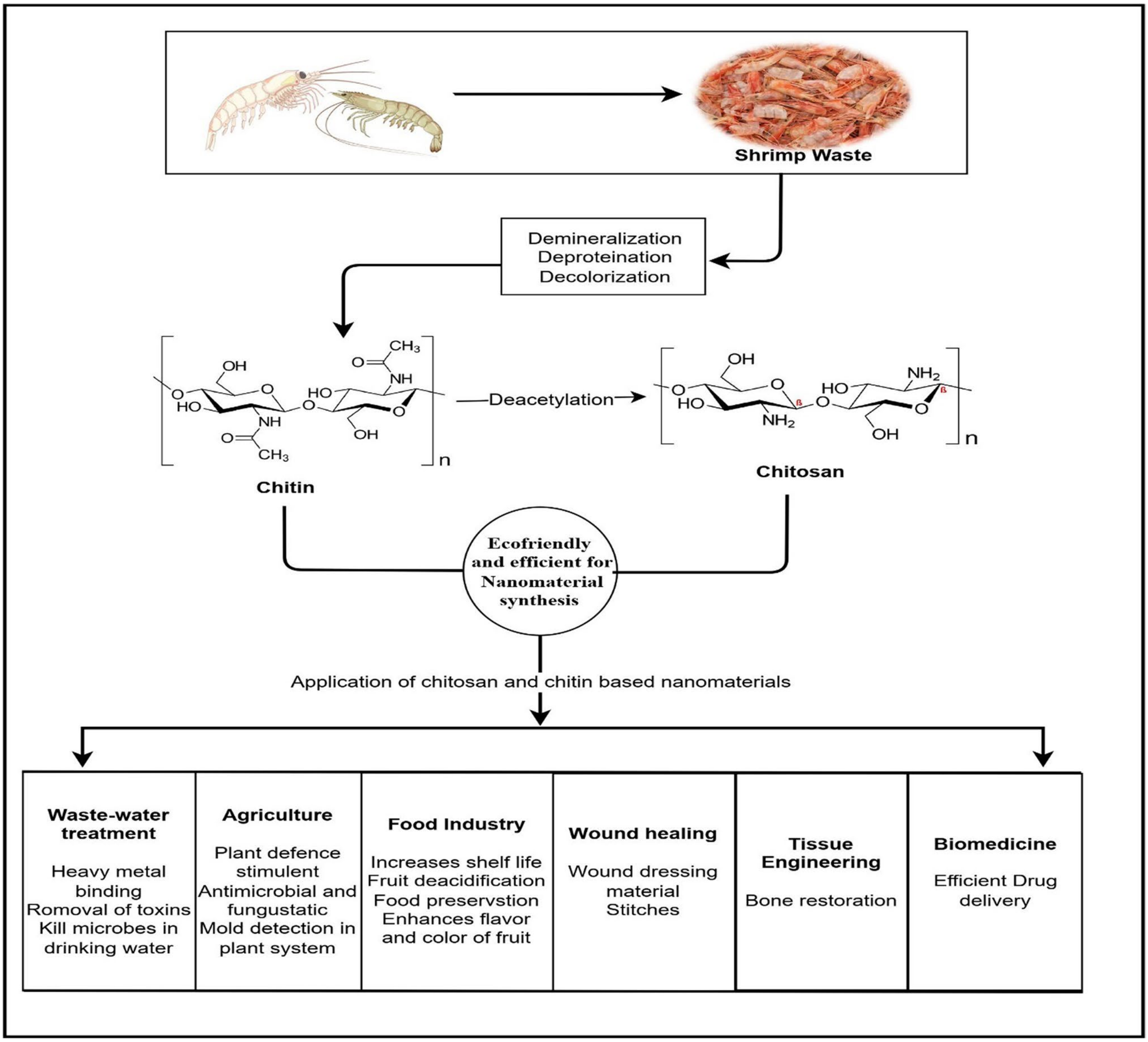

Fig. 3 Scheme for the synthesis of nanomaterials from SW and their applications

Conclusion

The article elucidates the rising concerns over the expansion of unutilized SW in major shrimp-producing countries of the world. The voluminous loss of nutrient-rich SW is a severe matter of concern. The chemical methods used for the valorization of SW for has serious major ecological disadvantages associated with it. Over the last decade, demineralization and deproteination processes for bioprospecting SW have been mediated using microorganisms. Fermentation and enzymatic action have emerged as a method of choice for processing seafood waste, mainly SW. The processing of SW has advanced applications in agriculture, pharmaceutical, cosmetic, and food industry—a step toward a green economy. The use of SW-derived bioactive compounds can contribute to environmental sustainability. Therefore, it is imperative to standardize and optimize the SW-processing methods for extracting quality products with minimum environmental effects.

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