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Abstract

Background

Crabs are one of the most diverse groups of crustaceans. Both fresh and marine crabs are an excellent source of many nutrients that are important for human health. Because of their unique flavour and delicious taste, crab meat and novel crab-based processed products are quite popular; hence the demand is increasing consistently in the domestic and global market. Further, crab processing generates a large quantity of liquid and solid waste creating disposal and land fill problems. To overcome the environmental impacts thereof, it is necessary to recycle and reuse these underutilized yet economically potential discards or by-products.

Scope and approach

Even though having immense potential in terms of nutrients and offering unique flavour profile, the importance of crab often goes unnoticed. However, crabs had less special mention and are mostly considered along with other crustaceans, wherein shrimps and lobsters are debated at length. Further, crab processing generates a large quantity of by-products and solid wastes, predominantly rich in chitin. Therefore, there is a great interest for valorisation of crab processing by-products that possess biologically active products with wide applications. In light of the above, this review highlights the nutritional aspects, flavour profile, quality and health benefits of crab meat including the acceptability of crab-based value-added products. The diversified applications of valuable products derived from crab processing bio-wastes are also discussed.

Key findings and conclusions

Crab meat is rich in protein, essential amino acids, long chain omega-3 fatty acids, and also an excellent source of vitamins and minerals. The uniqueness in taste and pleasant flavour properties of crab meat is due to volatile, non-volatile aroma and taste components, hence highly accepted by the consumers. Different innovative preservation technologies are suggested to improve the quality, safety and shelf-life of crab meat and crab-based value-added products. Further, crab processing wastes possess several high-value bioactive compounds. Green extraction is recommended for valorisation of these bioactive compounds (derivatives of chitin, protein hydrolysates and enzymes, lipids, carotenoids etc.) that have enormous applications in agriculture, environment, food, textile, pharmaceutical and other biomedical fields.

Key words: Crab, meat, nutrition, flavour profile, health, valorised products, processing wastes

1. Introduction

The demand for supply of safe and high quality of protein foods is increasing day by day with the increase of human population in the world. This situation is more important in developing countries where there is a wide spread of malnutrition and lack of quality foods. Hence, to meet such demand of protein requirement, foods from non-conventional sources are being explored ~~to~~ increase the production and supply. In aquatic ecosystem, fish and other edible aquatic species are well recognized for their rich protein content and are widely used as quality food supplement. Amongst the edible aquatic species, crustaceans that include shrimp, crab, lobster, crayfish, barnacles and krill are invertebrates with segmented bodies and have great commercial importance commanding high price both in the domestic and international markets (Venugopal & Gopakumar, 2017).

Crabs are one of the most important sources of food item and rank third only after shrimps and lobsters in terms of global seafood production (Narayanasamy et al., 2020). Many crab varieties are quite popular for their nutritional richness, flavour and esteemed delicacy, and also the value of fishery they support (Wang et al., 2018). Because of the uniqueness in meat quality, discernible qualities of taste and flavour, crabs meat is a preferred food item and occupies a special place among seafoods in restaurants across the countries (Anupama, Laly, Kumar, Sankar, & Ninan, 2018; Sreelakshmi, Manjusha, Vartak, & Venkateshwarlu, 2016). Moreover, crab meat is highly nutritious and healthy (Maulvault et al., 2012; Xie & Liu, 2020). Apart from being a rich source of highly digestible protein, essential amino acids, free amino acids, unsaturated fatty acids especially long chain omega-3 fatty acids, glycosaminoglycans, crab meats are also an excellent source of vitamins and minerals, particularly calcium, iron, zinc, potassium and phosphorus (Mandume et al., 2019; Premarathna et al., 2015; Venugopal & Gopakumar, 2017; Wang et al., 2018; Yogesh Kumar, Dineshbabu, & Thomas, 2019). Many bioactive components with specific functions were also reported in crabs (Balzano, Pacetti, Lucci, Fiorini, & Frega, 2017; Hamdi, Nasri, Dridi, Li, & Nasri, 2020; Kang, Lee, Seo, & Park, 2019). Due to these properties, meats and other components of crab are extensively being used as food components, flavour enhancers and as raw materials for design and development of various crab products with special taste and flavour.

Crab processing also generates a large/sizable quantity of potentially recoverable food-grade by-products and discards (shells, viscera, and residual meat remaining in the slabs and legs). A number of value-added products are being developed using these residual materials (Istiak, 2018;

Lorentzen et al., 2018; Tremblay et al., 2020). Further, undersized claws, legs and viscera could be potential raw materials for value-added product development. These are also good source of high-quality proteins, lipids components, pigments, and small biomolecules like marine oils, calcium, enzymes, antioxidants, flavorings, and pigments having health-promoting properties with potential applications in the food industry (Venugopal & Gopakumar, 2017; Tremblay et al., 2020). In addition, the shell materials from crabs are also good source of chitinous materials like chitin, chitosan, and chitooligosaccharides which have potential applications in many fields (Hamed, Özogul, & Regenstein, 2016; Shahidi, Varatharajan, Peng, & Senadheera, 2019). Recently, medicinal properties of various shell extracts, protein and peptides of crabs were reported to have antimicrobial, antitumor and immunomodulatory activities (Al-Shammari, Yaseen, Al-Alwaji, Raad, & Dawood, 2017; Bernabé et al., 2020; Long, Chen, & Wang, 2021; Narayanasamy et al., 2020; Rainey, Fukui, Mark, King, & Blitz, 2021).

Even though having immense potential offering health benefits, information on the nutritional composition, value-added processed products and utilization of by-products is generally scattered and not available comprehensively at one place in the literature. Sometimes, crabs are discussed along with other crustaceans under shellfish processing, wherein shrimps and lobsters are discussed at length and crabs don't find a special mention and their importance often go unnoticed. Hence, the main purpose behind this review is to highlight the nutritive value, flavour profile, various aspects on quality, safety and shelf-life of crab meat, and crab-based value-added food products. Further, the bioactive compounds and biomaterials obtained through valorisation of crab processing wastes and their applications in emerging fields of science are also discussed in this paper.

2. Brief overview on common crab species

Crabs are a distinct group of decapod crustaceans and known to thrive in a wide variety of habitats, in almost all the niches of the world, except Antarctica (John et al., 2018; Rana, 2018b; Trivedi, Trivedi, Vachhrajani, & Ng, 2018). About 7,000 species of crab are reported with 20 % in freshwater (streams, rivers, lakes, ponds, swamps), and rest in marine (swamps, estuaries/mangroves, seashore, deep sea), intertidal, terrestrial and semi-terrestrial (tree-climbing, forest floor, dry cave and even desert) habitats (Ng, 2017; Tsang et al., 2014). While most of the crabs are for food purpose and consumed in many corners of the world, the freshwater and marine crabs (Indo-Chinese potamid crabs of the genus Demanietta) have recreational, and ethno-medicinal values (Jelin & Keerthika, 2017; Rana, 2018a). Whether, farm raised or wild caught, crabs are commercially marketed throughout the world either as live or sold as crabmeat. However, the market price of edible fresh or marine water crab is mostly determined based on the factors such as size, age, weight, origin, and gender (Tang et al., 2020).

Some of the important commercially viable and valuable crab species are Dungeness crab (*Cancer magister*) of the Pacific coast, blue crab (*Callinectes sapidus*) of the Atlantic coast, brown edible crab (*Cancer pagurus*) of the British and European coasts (Ferdoushi, XiangGuo, & Hasan, 2010), mangrove or mud crab (*Scylla serrata*), Jonah crab (*Cancer borealis*), black stone crab (*Menippe mercenaria*), snow or red-tanner crab (*Chionoecetes opilio, C. japonicus*), coconut crab (*Birgus latro*), crucifix crab (*Charybdis feriatus*), Gazami crab (*Portuns trituberculatus*), green crab (*Carcinus maenas*), Chinese mitten crab (*Eriocheir sinensis*), swimming crab (*Portunus pelagicus*), soldier crab (*Mictyris brevidactylus*), Atlantic rock crab (*Cancer irrorutus*), Alaska king crab (*Paralithodes camtschaticus*, *P. platypus*, and *Lithodes aequispinus*), Columbus crab (*Planes minutus*), red or golden crab (*Geryon quinquedens* or *G. fenneri*) etc. (Anupama et al., 2018; Se Kwon Kim & Venkatesan, 2014; Kourantidou & Kaiser, 2021).

3. A brief summary on the nutritional aspects and health benefits of crab meat

Among crustaceans, crabs are of great commercial importance having nutritional value and occupy third rank only after shrimps and lobsters (Narayanasamy et al., 2020). By virtue of the meat quality and unique flavour, crab meat is a favoured delicacy and much in demand commanding high prices both in domestic and international markets (Istiak, 2018; Torres, Cortez, & Gaveria, 2017). Since nutritive value of any edible organism is reflected in its biochemical contents, the chemical composition is paramount. The chemical composition and nutritive value of meat from different crab species has been widely studied (Jeyalakshmi Kala & Chandran, 2014; Premarathna et al., 2015). Crab meat contains proteins, highly unsaturated fatty acids and is a rich source of valuable minerals, particularly calcium, copper, selenium, chromium, iron, zinc, potassium and phosphorus as well as water- and fat-soluble vitamins (Barrento et al., 2009; Wang et al., 2018).

The biochemical constituents of different fresh water and marine crab species in terms of moisture, protein, crude lipid and ash content and a wide variation thereof as reported by various studies are summarised in **Table 1**. The inter and intra-species difference in biochemical composition could be due to the influence of habitat (cultured *versus* wild), food source, seasonal and climatic changes, biological differences (species, size, age, sex, stage of maturity, gametogenesis and spawning cycle), and environmental factors (temperature, salinity, and contaminants (He et al., 2017; Jiang, Wang, Cheng, & Wu, 2020; Wu et al., 2020). For example, in a comparative study on biochemical composition of fattened and natural mud crab (*S. serrata*), Sarower et al. (2013) reported fattened crabs as nutritionally better with higher protein values irrespective of sex and size. The moisture and ash contents were, however, higher in natural mud crabs. Biochemical constituents of brown meat (mainly gonads and hepatopancreas) are reported to differ significantly from muscle, white meat in claws and legs of crabs (Maulvault et al., 2012). Variation in temperature also significantly influences the quality and flavour substances of crab. In a study on mud crab, *Scylla paramamosain*, Tang et al. (2020) reported that higher temperature induced the accumulation of flavour substances in gonads, while lower temperature facilitated its accumulation in muscles and hepatopancreas. Comparing the biochemical constituents in edible parts of wild-caught and rice-field male Chinese mitten crab (*E. sinensis*), Wu et al. (2020) found that edible tissues of wild-caught crabs were better in taste and had higher content of umami amino acids, minerals, mono and polyunsaturated fatty acid than rice-field crabs. In a study on female and male crab (*C. pagurus*), Barrento et al. (2009) recorded maximum yield of brown meat, essential amino acids (EAA) in muscle, fat and cholesterol in ovaries, eicosapentaenoic acid in male gonads during autumn as compared to other seasons. The hepatopancreas of green crab (*Carcinus mediterraneus*) had lipid content as high as 23%, whereas it was only 1% in its claw meat (Cherif, Frikha, Gargouri, & Miled, 2008). For the nutritional composition, a study investigating blue crab (*C. sapidus*) revealed that claw meat had higher protein than both hepatopancreas and breast meat whereas mineral contents (calcium, magnesium, phosphorous, potassium and sodium) of all edible parts varied significantly (Küçükgülmez et al., 2006). Habitat also plays a significant role in determining the biochemical composition of the same crab species (*C. feriatus*), inhabiting in both marine and estuary ecosystem. The crabs from marine sources exhibited highest protein and lipid contents whereas crabs caught from estuary waters had higher carbohydrate level (Jelin & Panju, 2017). A study on chemical composition of different brachyuran crabs from various habitats by Kala and Chandran (2014) reported higher values of protein (23.23%) in marine crab (*P. pelagicus*), whereas it was the lowest (13.23%) in *Cardisoma carnifex*, a species of terrestrial crab. The authors also reported low carbohydrate content in freshwater crab, *Barytelphusa cunicularis* compared to land crab (*C. carnifex*). The influence of gender on biochemical composition of edible crab, *Podophthalmus vigil* has also been investigated. It was found that female crabs were nutritionally rich in terms of protein, lipid and ash contents than berried female and male crabs (Soundarapandian, Ravichandran, & Varardharajan, 2013).

The rearing conditions (outdoor soil pool and indoor cement pool) also influence the taste components and flavour quality of crab. On comparing the effects of culture methods and conditions on the flavour of female crab (*P. trituberculatus*), Song et al. (2019) reported that indoor breeding significantly increased the total content of EAA, and enhanced umami taste quality of the crab meat and gonads compared to outdoor breeding. Likewise, wintering behaviour also affected the composition and content of non-volatile flavour related substances in edible parts of crab (*S. paramamosain*), with decreased content of flavour amino acids in hepatopancreas, and muscle whereas it increased slightly in gonad (Tang et al., 2020). The factors affecting the taste components and flavour quality of crab are vividly discussed in Section 4.

The biochemical constituents of crabs also vary depending upon their sizes/grades. In comparing the effects of different sizes/grades (≤ 150 g to 249 g) on the nutritional value of the edible parts (hepatopancreas, gonads, and muscle) of adult male Chinese mitten crab, *E. sinensis*, Wang et al. (2019) concluded that crabs in mid-weight range (150–200 g) have the highest nutritional quality, in terms of fatty acids and well balanced EAA composition, compared to other grades.

Identifying nutritional values of any product not only gives an idea about its quality but also helps in ascertaining the associated health benefits that can offer. As far as crab is concerned, the quality of meat protein is comparable with finfish due to a higher level of free amino acids. The meat is very digestible, as lacks connective tissues, and recommended for people of all ages, especially elderly. The long chain omega-3 fatty acids of crab meat is more beneficial to health, as can be used immediately, compared to short chain variety found in refined oils. Besides having anti-inflammatory properties, omega-3 fatty acids reduces the risk of heart attacks and strokes by preventing low-density lipoprotein formation, or "bad" cholesterol from adhering to the arterial walls (Bu, Dou, Tian, Wang, & Chen, 2016; Chaddha & Eagle, 2015; Mori, 2017).

The selenium content of crab, which is stated to be almost three times higher than cod and twelve times that of beef meat, is an excellent source of antioxidants. The selenium is essentially required for brain and endocrine tissues (Avery & Hoffmann, 2018; Ojeda, Carreras, Díaz-Castro, Murillo, & Nogales, 2019) and reduces the risk of cancer by preventing oxidative damage to the cells (Tan, Mo, Lau, & Xu, 2019). Crab meat with low caloric content, is often termed as calorie counter's dream meat. As carbohydrate-free, it is termed as a great choice for persons suffering from diabetes.

Crab meat contains a healthy amount of the water-soluble vitamin, folate (vitamin B_9). According to the reports available, a diet with adequate amounts of folate can help in reducing the levels of a sulfur containing amino acid called homocysteine in the blood, which in turn prevents the risk of cardiovascular diseases, heart strokes, and brain disorders, like Alzheimer's and Parkinson's diseases (Craenen, Verslegers, Baatout, & Abderrafi Benotmane, 2020; Guo, Ni, Li, Wang, & Yang, 2019). Crabs, particularly from marine sources, are known to contain a group of fat-soluble pigments, carotenoids and the red-orange-coloured astaxanthin and its esters (Li et al., 2020; Venugopal & Gopakumar, 2017). As astaxanthin with potent antioxidant activity improves immunity and plays an important role in preventing cardiovascular and other degenerative diseases, these are widely being used as feed additives and in food industries as well (Zhao et al., 2019).

From the above, it is clear that crab meat could be a very good add-on to the diet, as it possesses almost all the essential nutrients, and elements (from omega-3 fatty acids to selenium and protein and vitamin B) that are required for proper functioning of the human body. Consumption of crab meat offers numerous health benefits because of its ability to increase cognition, protect the heart, reduce inflammation, strengthen bones, boost the immune system, stimulate circulation, and detoxify the body. Besides fulfilling the nutritional requirements and providing health benefits, crab meat is believed to have medicinal values and traditionally used to cure chronic fever, asthma, malaria, diarrhoea and dysentery, typhoid, bronchitis, pneumonia, epilepsy, diabetes, skin diseases, boils, burns, wound healing, osteoporosis, reproductive malfunction etc. (Rana, 2018a; Roy, 2014).

4. Flavour profile of edible crab products

Flavour is one of the prime components of sensory attributes and often termed as "The feel-good factor" based on which consumers accept or reject any food product. The flavour component of food denotes to the complex combination of sense of smell, taste, and trigeminal sensory sensation, which is experienced by the consumer during the food tasting process (Song et al., 2019). As far as crab meat is concerned, it is well liked, highly accepted and extremely popular among consumers due to its unique taste and pleasant flavour properties. The volatile and non-volatile aroma compounds as well as taste components present in the food are intimately related to its quality and flavour. The taste components mainly include nucleotides, organic acids and bases, free amino acids, sugars, and inorganic salt compounds; whereas the volatile aroma components of crabs are carbonyls (alcohols and ketones) and aromatic compounds, aldehydes, alkanes, furans, nitrogen and sulfur containing substances and lipids (Jin, 2011; Song et al., 2019).

Although various volatile compounds are found in crab meat, few of them have contributory role to the aroma (Gu, Wang, Tao, & Wu, 2013; Yu & Chen, 2010). The analysis of different odour-active compounds in Chinese mitten crab by Chen and Zhang (2010) establish that the major components are mainly trimethylamine (TMA), dimethyl sulfide, 1-octen-3-one, dimethyl trisulfide, 1-octen-3-ol, 3-(methythio)-propanal, benzaldehyde, and 2-acetylthiazole. According to the authors, the two most crucial odorants with high odour intensity were dimethyl sulfide having crab meat aroma and TMA with typical odour of fish and amines. In a study involving edible parts (meat, gonad and hepatopancreas), electronic tongue (E-tongue) and electronic nose (E-nose) detected the differences in flavour profile (odours and tastes) among three Chinese mitten crabs like wild-caught, Yangcheng and Chongming crabs (Wang et al., 2016). The authors reported that alcohols, aldehydes and aromatics as the major volatile components in crab meat whereas gonads and hepatopancreas had higher level of aldehydes and aromatics.

A study conducted by Chung and Cadwallader (1994) in blue crab (*C. sapidus*) indicate that 2,3-butanedione, (Z)-4-heptenal, 2-acetyl-1-Pyrroline, and 3-(methyl-thio) propanal are the most potent aroma compounds. Using two olfactometric methods, Yu and Chen (2010) identified five important compounds *viz*. 2,3-butanedione (creamy, caramel), 2,5-dimethylpyr-azine (roasted, nutty), 3-methylbutanal (chocolate), 2-acetyl-1-pyrroline (popcorn, nutty), and 2-acetylthiazole (roasted, sulfury) as the major contributors to the aroma of steamed mangrove crab (*S. serrata*). Similarly, Song et al. (2019) detected 74 odour compounds that include carbonyl (aldehydes and ketones) and aromatic compounds, alkanes, alcohols, furans, nitrogen-containing and sulphur-containing substances in the gonads and meat of swimming crab cultured in both indoor and outdoor conditions. Wu et al. (2014) also detected near about 40 aroma compounds in four edible parts of Chinese mitten crab (*E. sinensis*) and among them, aldehydes were major contributors of flavour.

Again many researchers have reported that the non-volatile taste active compounds such as soluble sugars, succinic acid, free amino acids, organic acids and flavour 5'-nucleotides play an important role for unique pleasant aroma and a delicious taste of crab meat (Liu et al., 2018). Crabs and other aquatic products are reported to have some natural taste nucleotides; the main nucleotides that exhibit umami taste are 5'-Adenosine monophosphate (AMP), 5'-inosine monophosphate (IMP) and 5'-guanosine monophosphate (GMP) (Shi, Wang, Wu, & Shi, 2020). These non-volatile taste components such as free amino acids and nucleotides (AMP, IMP and GMP) also play a vital role in the special taste of crabs (Tao et al., 2018; Wang et al., 2016). Furthermore, the amount of free amino acids, apart from influencing the freshness of the food, act synergistically with nucleotides and play an important role in enhancing the umami taste and make the food taste more delicious (Song et al., 2019).

Umami is recognized as the fifth basic taste other than four basic tastes of food such as salt, sweet, sour and bitter and is one of the most important flavour characteristics of crab meat products (Marcus, 2015; Wang et al., 2019). Various disodium salts of 5' taste nucleotides such as IMP, GMP, AMP etc. can produce umami, whereas among free amino acids; glutamic and aspartic (Asp), known as monosodium glutamate (MSG)-like components also have umami effect (Tang et al., 2020). Among 5' taste nucleotides, IMP and GMP act as intense flavour-enhancers of the umami taste and even much stronger than MSG but the concentration of AMP in crab products is critical for its contribution towards taste profile (Chen & Zhang, 2007). It is interesting to note that IMP at low concentration is responsible for sweetness but no umami taste; however, it elicits the umami taste when there is a synergistic interaction between AMP and IMP (Liu et al., 2018).

Sweetness is another major flavour characteristic of crab based edible products, and free amino acids such as glycine (Gly), alanine (Ala), proline (Pro), threonine (Thr) and serine are reported as the main contributors (Zhao, Wu, Wang, Wu, & Wang, 2016). However, as the contents of free amino acids are quite variable and depend on many factors, the levels of sweetness of edible products from crabs are also variable. Chen and Zhang (2007) reported that out of the total free amino acids content (20.9 mg/g) in meat of Chinese mitten crab (*E. sinensis*), only three amino acids such as arginine (Arg), Gly and Ala accounted for more than 70% of the total free amino acids. The authors also pointed out that although snow and mud crab have similar amino acids concentrations, but they are characterised with intense sweetness flavour due to higher contents of Gly, Arg, Pro and Ala. Besides sweetness, reports are also available regarding slightly bitter taste of edible parts of mud crab (*S. paramamosain*) and this is mainly due to the action of some bitter amino acids likely Arg, lysine, tryptophan and tyrosine (Tang et al., 2020; Tao et al., 2018).

Other components like organic acids (lactic acid, succinic acid etc.) related to the flavour profile are also described in aquatic products, including crab. In a recent study, lactic acid was reported to enhance the taste and flavour of mud crab to a certain extent, but at lower concentration (Tang et al., 2020). Besides, few other studies have indicated the possible role of taurine (2-aminoethanesulfonic acid), a bioactive component contributing to flavour of crabs. Known for many health properties, taurine was found to be higher in mud crabs, especially in the hepatopancreas and its accumulation was dependent on temperature (higher level in low temperature) of rearing environment (Wang et al., 2019). Upon critically analysing the sensory reports and data of high-end sophisticated instruments such as E-nose and E- tongue, it could be deduced that flavour properties of crab products are highly variable and influenced by many factors.

5. Quality, safety and shelf-life of crab meat

Like other aquatic products, the demand for fresh, frozen crab meat and processed crab meat products have increased dramatically over the last few years both in the domestic and international market. However, fresh crab meat is perishable in nature and at higher risk of spoilage due to high water activity and moderate pH. In general, most of the crab products have a refrigerated shelf-life of five days in aerobic conditions (Lorentzen, Skuland, Sone, Johansen, & Rotabakk, 2014). The products lose their flavour and colour within 10-14 days even in good storage conditions due to microbial growth and enzymatic activity (Galetti, 2010). In fact, the quality and shelf-life of crab products depend on many factors, including harvesting methods, temperature, processing types, preservation methods, storage, and other conditions. The handling methods employed after harvesting play a crucial role on the microbiological, physical and biochemical changes which in turn determine the microbial quality and shelf-life of both raw and processed products (Olatunde & Benjakul, 2018; Ronholm, Lau, & Banerjee, 2016; Venugopal & Gopakumar, 2017). Apart from high water activity and moderate pH, microbial contamination acquired during post-harvest processing and storage is one of the factors for spoilage of the product (Getu & Misganaw, 2015).

The chemical and enzymatic reactions of the meat during storage coupled with metabolic activity of microbes trigger the production of amines, sulphides, alcohols, aldehydes, ketones and organic acids affecting the freshness and organoleptic properties of crab meat (Anupama et al., 2018; Robson, Kelly, & Latchford, 2007). Similarly, the problems that are often encountered with pasteurized, frozen crab products are lipid oxidation, dehydration, loss of juiciness, colour, and excessive exudate during thawing (Dima, Baron, & Zaritzky, 2016; Ye et al., 2021). These changes not only bring in quality issues but also result in a short shelf-life of the fresh and frozen crab products, like other seafood products (Erkan, 2014; Lorenzo, Tomac, Tapella, Yeannes, & Romero, 2021).

To avoid or prevent microbial growth ensuring food safety and with an aim to improve shelf-life, food technologists and researchers adopt various measures through application of preservatives, preservation and hurdle techniques, either individually or in combination. Although traditional preservation techniques such as drying, salting, smoking, freezing, canning, pasteurization, chilling, chemical treatment and packaging are employed in maintaining the quality and safety, controlling spoilage by microorganisms and retaining sensory attributes of the products is still a challenge (Kim & Venkatesan, 2014; Ronholm et al., 2016).

In recent days, consumers are becoming more health conscious and demand minimally processed food with extended shelf-life and assurance of safety (Das, Nanda, Das, & Biswas, 2019). To satisfy the consumer’s demand for safe crab products having long shelf-life, processors are exploring innovative technologies (**Fig. 1**) to maintain the desired quality and safety of products at various stages of processing (Olatunde & Benjakul, 2018). These novel, innovative thermal and non-thermal technologies not only reduce the microbial contamination, but also improve the shelf-life and preserve the nutritional, culinary and sensory attributes of crab products (Anupama et al., 2018; Dima et al., 2016; Ronholm et al., 2016). For example, sous-vide cooking is an innovative thermal processing technology where foods are cooked in vacuum plastic pouches at a precise time and controlled temperatures. This process has an edge in respect of doneness and texture over traditional thermal processing (Baldwin, 2012; Ruiz-Carrascal, Roldan, Refolio, Perez-Palacios, & Antequera, 2019). Processing of foods in heat-stable vacuum package with controlled temperatures maintains the quality (taste and nutrition) and enhances the shelf-life (Bhat, Morton, Zhang, Mason, & Bekhit, 2020). In a recent study, crab lump meat was processed using sous-vide cooking in different combinations of temperature and time (75, 80 & 85 °C and

1& 2 h) to study its quality and shelf-life (Olatunde & Benjakul, 2021). The authors reported that this systematic approach of cooking (for 1 h at 80 °C) could maintain meat quality without altering protein pattern, had least effect on color and lipid oxidation and also improved shelf-life (>60 days) of crab lump meat by inactivating microorganisms.

Some of the non-thermal and most well-known technologies are high hydrostatic pressure (HHP), high pressure processing (HPP), radio-pasteurization, phage treatment, etc. (Huang, Wu, Lu, Shyu, & Wang, 2017; Keethadath, Kappalli, Gayathri, Thomas, & Anilkumar, 2019; Luo et al., 2020; Martínez-Maldonado, Velazquez, Ramírez de León, Borderías, & Moreno, 2020; Mei et al., 2018). Again, natural antioxidants, antimicrobial compounds, bio-preservatives and packaging (active, biodegradable, vacuum, modified atmosphere packaging-MAP) are some of the alternative solutions and currently being applied to inhibit the growth of microorganisms and to improve the meat quality (Das et al., 2020; Domínguez et al., 2018; Umaraw et al., 2020). Among non-thermal processing methods, HPP is reported to have promising results as far as crab meat quality and safety are concerned. In HPP or HHP, there is inactivation of pathogenic microorganisms and enzymes present in foods due to application of high pressure (100–600 Mpa). In a recent study, high pressure processing (300 MPa/20 min/25°C) was found to improve the quality and safety of vacuum-packaged crab meat by inhibiting the microbial growth and maintained the sensory and other biochemical properties (Ye et al., 2021). In another study, whole cooked brown crab (*C. pagurus*) treated with 900W ultrasonic bath for 45 min at 75 °C was found to have increased salt extraction (low salt in meat) and dirt removal (cleaner crab) with greater microbial reduction and improved cooking time at the same F value (Condón-Abanto, Arroyo, et al., 2018). Electron beam irradiation did not influence the key volatile flavour compounds of crab meat (*Ovalipes punctatus*) but produced off-odour at ≥7 kGy whereas sensory scores decreased with increase in radiation dose (Mei et al., 2018). Swimming crabs (*P. trituberculatus*) preserved using super chilling and MAP with 60% CO_2 were found to have improved quality and shelf-life (Sun et al., 2017). In another study, Luo et al. (2020) reported that combined treatment (antimicrobial and natural chemicals) was effective in reducing foodborne pathogens, inhibited microbial spoilage, and maintained the quality and safety of crab paste under frozen storage conditions (−20°C). These technologies not only help in preserving the freshness of products by keeping their texture and flavour unchanged but also destroy the microbial pathogens that spoil the food (Ekonomou &

Boziaris, 2021; H. W. Huang et al., 2017; Martínez et al., 2017; McClements, Das, Dhar, Nanda, & Chatterjee, 2021).

Various researchers have used these traditional and innovative non-thermal preservation technologies to improve the quality, safety and extend the shelf-life of crab products. The effectiveness of these technologies in terms of dose, duration and their mode of action for overall improvement of crab products are summarized in **Table 2**.

6. Crab meat based novel food products

6.1 Value-added products and their quality attributes

Crabs are popular food items. The crab-based products are mainly prepared utilising crab meat (cooked, roasted, deep-fried, steamed, stewed, boiled or baked) as whole after removing the meat portion from the exoskeleton, or separating the meat from claws, legs and body. These portions are added at different levels to develop a variety of value-added products, based on the taste and preference of consumers. In a study, Baxter (2007) used previously cooked Jonah crab (*C. borealis*) mince to develop a new food product by preparing three varieties of crab appetizers *viz*. Italian, Curry, and Jalapeno. The study concluded that all the varieties of crab appetizers, a cross between a crab cake and nuggets were acceptable by the consumers with very high overall liking scores. Similarly, pastas developed using underutilized mince (10 to 20%) from Jonah crab (*C. borealis*) were highly appreciated (Gillman & Skonberg, 2002). Even pasta flavour was developed utilizing the shell wastes from the flower crab (*P. pelagicus*) by mixing emulsifiers such as corn starch and sugar palm flour (Rahmawati, Saputra, & Abdillah, 2019).

There are also a number of assorted dishes prepared using crab meats available in different parts of the world. A sharp increase in popularity of crab products and their availability in restaurants could largely be due to the availability of low-cost imported crab meat and distinct flavour that favour the consumer to enjoy and relish the product. Quite popular among them are Empanada or pastelitos (South American stuffed and fried pastry) containing 30, 50 and 70 % green crab (*C. maenas*) mince (Galetti et al., 2017); blue crab crab-cakes with processing by-product of various combinations of claw mince/meat (CMM), surimi, and functional soy protein concentrate (Lee, Meyers, & Godber, 1993); extruded snacks with blends of Atlantic rock crab (*Cancer irradians*) processing by-products (0%–40 %), corn meal and potato flake (Murphy et al., 2003); ready-to-serve bread spread from blue swimmer crab (*P. pelagicus*) meat (Biji et al., 2013) and crab based pasta prepared using 10 or 20 % mince from crab processing by-products (Gillman & Skonberg, 2002). Other important products are fully cooked green crab (*C. maenas*) meat mince patties with 1, 2 or 4 % transglutaminase (Galetti, 2010); fish paste prepared with red snow crab (*C. japonicus*) leg-meat powder (3, 6, 9, or 12 % concentrations) (Kim, Jung, Jung, et al., 2016); thermally processed ready-to-serve sandwich spread prepared from mud crab (*S. serrata*) meat (Sreelakshmi, Manjusha, Nagalakshmi, Chouksey, & Venkateshwarlu, 2015); ready-to-eat crab koftha or fried crab balls (Abhilash, Ravishankar, & Srinivasa Gopal, 2013); noodles with lyophilized leg-meat powder (2, 4, 6, 8, or 10 %) of red snow crab (Kim, Jung, Kim, et al., 2016); meat dip with cooked blue swimming crab (*P. pelagicus*) and sodium acetate (Lohalaksanadech & Sujarit, 2011); patty with red-tanner crab (*C. japonicus*) paste (Heu, Choi, & Kim, 2005); value added (herb flavoured and a chilli tomato) crab stock from cooking water of blue swimmer crab (*P. pelagicus*) (Choo, 2009) etc. Interestingly in a recent study, caroteno-proteins extract (CPE), a co-product from blue crab shell was found to have both antioxidant and antimicrobial activity. Incorporation of CPE in turkey meat sausages containing reduced quantity of nitrites significantly stabilized the color of sausages by reducing metmyoglobin formation and extended the shelf-life, inhibiting lipid oxidation and microbial growth (Marwa Hamdi et al., 2018). The formulation of various crab meat and other co-products based novel food products and their quality attributes in terms of sensory evaluation and physico-chemical parameters is given in **Table 3**.

6.2 Ethnic and other crab-based food products

Various crab-based products are being produced through ethnic food fermentation process, one of the oldest methods of food preparation and preservation. This not only improves the quality characteristics and nutritional value but also enhances the shelf-life. ‘*Japangangngatsu*’ is an indigenous fermented food product made from mud crab and is consumed as an important part of the diet in Nagaland, India (Deb & Jamir, 2020). Similarly, crab sauce prepared by curing and fermenting soldiers crab meat is a traditional umami seasoning. These fermented products have typical umami taste and are quite popular and preferred among local people and tourists (Liu, Xia, Wang, & Chen, 2019; Shivanne Gowda, Narayan, & Gopal, 2016). Because of the unique flavour attributes, crab meat and its component are now a days incorporated in a variety of food products to improve their nutritional profile and acceptability. Besides, various thermal processed crab-based products like canned and pasteurized colossal crab meat, jumbo lump, claw meat, claw fingers etc. are also widely available in the market (Biji et al., 2013). Furthermore, many food processing companies are now coming out with new innovative product lines with more exotic flavours.

7. Sensory attributes and acceptability of crab-based products

Sensory attributes are often considered as key determinants for evaluation of the quality and acceptability of food products and have a great impact on the willingness of a consumer to accept or reject the product (Das et al., 2020). Crab meat-based food products are quite popular and widely accepted by consumers owing to their flavour and sensory attributes. Galetti et al. (2017) developed a novel food product, "empanadas" containing 30 %, 50 %, and 70 % green crab mince and evaluated its consumer acceptability. Sensory analysis indicated that empanadas had good mean overall acceptability score (6.5) and favourable 'willingness to purchase" score irrespective of the formulation (fried, stuffed pastries), indicating promising aspect for value-added green crab products. Development of value-added stocks such as herb flavoured and chilli tomato crab stock utilising crab cook water or concentrated liquid crab stock has also been reported (Thanzami & Lalhlenmawia, 2020). Upon sensory evaluation, although both the products were highly acceptable amongst the panellists, the chilli tomato crab stock was the most preferred one due to its more soup-like characteristics. Evaluating the sensory, texture and colour attributes of crab koftha (a traditional north Indian food consisting of whole cooked potatoes in spicy gravy) prepared after thermal processing in indigenous polymer-coated easy open-end tin-free steel can, Abhilash et al. (2013) concluded that crab koftha when processed had desirable firm texture and received very good acceptability scores. In another study, noodles prepared with different levels (2, 4, 6, 8 or 10 %) of lyophilized leg-meat powder from the red snow crab (*C. japonicus*) had improved redness, hardness, gumminess, chewiness with increasing level of crab powder (Kim, Jung, Kim, et al., 2016). Further, the noodles incorporated with 4 – 6 % crab powder had greater overall consumer acceptability.

In another study, Kim et al. (2016a) reported that leg-meat powder of red snow crab (*C. japonicus*) incorporated with 6 % level in fish paste had improved sensory attributes in terms of hardness, gumminess, springiness, and cohesiveness and increased physico-chemical properties. Evaluating a ready-to-serve thermal processed sandwich spread with the meat of mud crab, Sreelakshmi et al. (2015) reported that the product processed at higher temperature had better flavour and overall acceptability scores, although colour, odour, taste, and spreadability of the spreads were not significantly affected due to different time and temperature combinations. This might be due to the change in the volatile flavour compounds of fat in crab meat at high temperature processing. Crab meat nuggets with 0 and 15% rice flour has also been reported to have acceptability indices above 70% with 81.8% and 77.8% rates, respectively than the acceptance rate of nuggets with 30% flour (Da Silva & Da Silva, 2019).

Crab paste has also been used as a surimi gel source. The quality and freshness of crab paste depends on fermentation time as well as the level of TMA production and its incorporation in formulation influences the sensory attributes and nutritional quality of products (Chen, Ye, Chen, & Yan, 2016). For example, the incorporation of red-tanner crab paste in a new type of patties developed with surimi not only had increased sensory colour and flavour scores but also enhanced nutritional quality (Heu et al., 2005). A value-added snack food (Murukku or Chakli) developed with crab meat replacing rice flour was found to be delicious and highly acceptable by the panellists than snacks prepared with fish and egg (Anfal & Dhanya, 2020). Similarly, sensory evaluation of minced meat crab cake prepared with different combination of claw mince/meat, surimi and functional soy protein concentrate had increased crabby flavour, and decreased beany flavour when claw mince was increased in the formulation (Lee et al., 1993). The authors also noted a difference in crabby and beany flavour scores between crab cakes with claw mince/meat ratios of 25/75 and 50/50 and concluded that optimal ratio of claw mince and meat is needed to keep desirable flavours of the final formulation. These reports clearly indicate that crab meat plays a significant role in improving sensory properties and acceptability of crab meat based-products.

8. Valorisation of crab by-products/processing waste

Crab discards and by-products, mainly the liver (or hepatopancreas or brown meat) and shells are of interest to the processors, as they constitute more than 50% of the crab weight (Malaweera & Wijesundara, 2013). The brown meat is used as a source of flavouring for preparation of various crab (bases, stocks, and soups) and non-crab (fish sauce or fish paste) based food products (Goldhor & Regenstein, 2007). Crab shells (exoskeleton) are rich sources of valuable structurally diverse bioactive nitrogenous components (**Fig. 2**) and contain proteins, minerals (mainly carbonates of calcium and magnesium), pigments, flavorants, and chitin (Selva, 2020; Venugopal & Gopakumar, 2017; Xu, Nasrollahzadeh, Selva, Issaabadi, & Luque, 2019). Even cooking effluents of crab processing facilitates, often discarded as wastes, are concentrated using reverse osmosis and valorised into solid components, mainly proteins, minerals and flavour compounds. The solid components (retentates) can be used for product development and as natural aroma in the food industry (Tremblay et al., 2020). With increased efforts to augment the production of crab, more waste is now generated from the crab processing industry creating waste disposal problems and environmental concerns. To overcome the slow biodegradation process and environmental impacts thereof, these underutilized yet economic potential discards or by-products with remarkable biological properties are receiving much attention and are recycled and valorised to obtain nutraceuticals, bioactive derivatives, chitosan and oligomers, natural pigments etc. (Hamed et al., 2016; Shahidi et al., 2019), that have better functional properties and a variety of applications (**Fig. 3**). In fact, recycling of crab-derived bio-wastes for the production of value-added chemicals and materials not only reduces solid waste disposal and land fill problems but also diminishes the concerns of toxic threat, air and water pollution making the environment clean and healthy (Kim & Mendis, 2006; Mathew et al., 2020; Xu et al., 2019).

9.1. Chitin and its derivatives from crab discards and by-products

Chitin is one of the most abundant amino-polysaccharide polymers available in the world, but only after cellulose (Younes & Rinaudo, 2015). The chitin content of crab is reported to vary from 14 to 28 % on total dry weight basis, depending upon the species and other factors (Venugopal, 2016). Because of the ease of availability, cost-effectiveness and high biocompatibility, these polysaccharides from crab shell wastes are currently chemically modified, biotechnologically engineered or blended with other natural polymers to produce functionally diverse active derivatives (Yadav et al., 2019). One such derivative, obtained by partial deacetylation of chitin under alkaline conditions, is chitosan, and has enormous applications over chitin, the reason being its better solubility and compatibility (Hamed et al., 2016; Pighinelli, 2019; Younes & Rinaudo, 2015).

9.2. Applications of chitosan and its derivatives

Chitosan and its oligomers such as chitooligosachharides, chitobiose, N-acetyl glucosamine etc. are receiving much attention because of their physiological inertness and biological properties. Being non-toxic, hydrophilic, biocompatible and biodegradable, these materials can be easily processed into fine powder, flake, sponge, gel, membrane, bead, scaffold, film, fibril, fibre or particle forms (Ahmed & Ikram, 2016; Merzendorfer & Cohen, 2019) offering gel-forming, antimicrobial, antioxidant, anti-inflammatory, anticancer and metal chelating properties (Kim, 2013; Fereidoon Shahidi et al., 2019; Vazhiyil Venugopal, 2016). Because of these inherent and outstanding properties, chitosan and its derivatives are much in demand not only in the field of biotechnology, food, pharmaceutical, textile, cosmetics and agriculture industry but also have possible applications in environmental protection, wastewater treatment and biomedical devices (Morin-Crini et al., 2019; Zhou et al., 2021). Further, these are also used as a futuristic biomaterial in bone/teeth implants, tissue engineering, and drug delivery, among others (Bhattacharjee, Mishra, Rai, Parkash, & Kumar, 2019; Kabanov & Novinyuk, 2020; Merzendorfer & Cohen, 2019).

The role of chitosan as a functional ingredient in food and feed products conferring beneficial health effects to humans and animals is well recognised. With distinctive functional and bioactive properties and generally regarded as safe by the Food and Drug Administration, chitin and its derivatives have numerous applications in food product formulation, processing and packaging. Chitosan has excellent gelling, stabilizing, thickening, emulsifying properties of chitosan. Hence, chitosan-based nano or microencapsulation are now used for delivery of bioactive compounds (functional ingredients, antioxidant and antimicrobial agents) to improve the safety and quality of food products (Gallo, Naviglio, Armone Caruso, & Ferrara, 2016; Gutiérrez, 2017; Kumar, Mukherjee, & Dutta, 2020; Morin-Crini, Lichtfouse, Torri, & Crini, 2019; Silva, Souza, & Lacerda, 2019). Chitosan coating has also been demonstrated to have preservative and antimicrobial effect in muscle food system (Bonilla et al., 2018; Sotoudeh, Azizi, Hashtjin, Pourahmad, & Tavakolipour, 2019). Chitosan, used in low dosages as food supplements, has the ability to lower fat absorption which may help obese people in weight management (Huang, Liao, Zou, & Chi, 2020). The natural polymer is also an effective hypocholesterolemic agent, as it lowers triglycerides and more than 50 % of blood cholesterol levels from the body (Moraru, Mincea, Frandes, Timar, & Ostafe, 2018).

Considered as a source of prebiotic ingredient, chitosan and its oligosaccharides not only aid in improving the gastrointestinal function by stimulating the development of health promoting intestinal microflora, but also confers protective effects against infections (Silva et al., 2019). The antibacterial, antileishmanial, anti-inflammatory, antiatherosclerosis, antihypertensive, anti-tumor, anticoagulant and antidiabetic effects of chitosan and its derivatives for prevention and treatment of chronic diseases has also been reported by many researchers (Alishahi & Aïder, 2012; Kang, Skonberg, & Myracle, 2020; Ngo & Kim, 2014; Riezk, Raynes, Yardley, Murdan, & Croft, 2020; Sánchez-Machado et al., 2018). Likewise, crab hydrolysates are a good source of natural antioxidants and are reported to have antibacterial activities against both Gram-negative and -positive bacteria (Hajji, Ghorbel-Bellaaj, Younes, Jellouli, & Nasri, 2015; Shaibani et al., 2020). Even the hemolymph microbiota of marine crabs viz. *Charybdis lucifera, C. feriatus, Portunus sanguinolentus* and *P. pelagicus* are promising source of pro-biotics/antimicrobial agents (Sumithra et al., 2019).

Various cationic and anionic antimicrobial peptides such as lectin, proline, scygonadin, cryptocyanin, callinectin, scyllin have been isolated and characterised from hemocytes and seminal plasma of crabs that form an important means of host defense system to combat infections and diseases (Lorentzen et al., 2014; Yusof, Ahmad, & Swamy, 2017). Furthermore, anti-lipopolysaccharide factors have also been identified from the hemocytes of several crab species *viz*. *C. maenas*, *E. sinensis*, *S. paramamosain* and *C. sapidus*, that apart from neutralizing lipopolysaccharide exhibit broad spectrum antibacterial activities (Fredrick & Ravichandran, 2012; Yusof et al., 2017).

The derivatives of this biopolymer have potential to inhibit the activity of angiotensin converting enzyme, the enzyme associated with hypertension or high blood pressure (Auwal, Zarei, Tan, Basri, & Saari, 2018; Zhou et al., 2021). The bioactive peptides derived from enzymatically hydrolysed crab by-products (cephalothorax shells, digestive systems including hepatopancreas, and physiological liquid) are reported to have anticancer activity on several cancer cell lines (Doyen, Beaulieu, Saucier, Pouliot, & Bazinet, 2011; Shaibani, Heidari, Khodabandeh, & Shahangian, 2021). Chitin and its derivatives are stated to facilitate and accelerate healing process by protecting wound from bacterial invasion and subsequent proliferation (Morin-Crini et al., 2019). It has also been reported that polymer films prepared from chitin extracted by X-ray diffraction analysis from Philippine blue swimming crab (*Portunus pelagicus*) are more purer than the commercially acquired high purity chitin and has greater ultimate tensile strengths as compared to the commercially-available plastic film (Fernando, Poblete, Ongkiko, & Diaz, 2016). Further, chitosan in combination with scaffolds, nanomaterials, nanocomposites or nanofillers are used in biosensors and targeted drug delivery devices having biomedical applications that could enhance tissue and bone regeneration, facilitating wound dressings (Ahmed & Ikram, 2016; Moura, Mano, Paiva, & Alves, 2016). Development of a biosensor having industrial use has also been made possible by combining silver nanoparticles and graphene with chitosan that can detect hydrogen peroxide, a potentially dangerous by-product (Zhang, Han, Liu, Tang, & Tang, 2014).

Crab carapace also contains promising source of carotenoids, a group of fat-soluble pigments, with astaxanthin and its esters being the major components. These bioactives, with strong antioxidant capacity, are currently being used in functional food formulations (Nunes et al., 2021). Furthermore, carotenoids play an important function in reproduction; act as precursors of vitamin A, and enhancers of immunity. Animals including fish cannot synthesize carotenoids *de novo*, so these must be supplemented in diet to enhance muscle pigmentation, improve skin colour and market value (Maoka, 2020). Recently different modern innovative extraction technologies in combination with natural deep eutectic systems are being used to improve the extraction efficiency as well as yield of astaxanthin, a highly demanded carotenoid than conventional Soxhlet extraction method (Nunes et al., 2021; Rodrigues et al., 2020).

Crushed crab shells also act as suitable biosorbents and are effective in removal of heavy metals (copper, cadmium, chromium and lead) from surface and contaminated water (Aris, Ismail, Ng, & Praveena, 2014; Esguerra et al., 2018). Being natural, cost-effective and environment friendly, these have advantage over other conventional and high-cost technologies. Thermally active crab shells mainly contain calcium oxide which can be used and re-used as a low-cost catalyst up to 11 times in transesterification of palm olein for producing biodiesel (Boey, Maniam, & Hamid, 2009; Hülsey, 2018; Kayser, Pienkoß, & Domínguez De María, 2014). Chitosan is also effective in controlling plant pathogens, improves crop yield and minimizes post-harvest moisture loss in fruits and vegetables, thereby extending shelf-life of the agriculture and horticulture products (Badawy & Rabea, 2011; Morin-Crini et al., 2019; Romanazzi, Feliziani, Baños, & Sivakumar, 2017). Needless to say, chitin and its derivatives have a wide range of applications contributing significantly to the economics of crab processing industry. This is evident from the on-going research and development efforts on chitin derivatives at both academic and industrial level and number of research findings that are published almost every day in the form of scientific publications.

10. Conclusion and further recommendations

Crab meat commands high price and quite popular due to its delicious taste, unique flavour and richness in versatile food nutrients including proteins and essential amino acids, long chain omega-

3 fatty acids and micro-nutrients such as vitamins and minerals. However, crab meat and based novel food products are perishable in nature, hence different preservation techniques are applied to enhance the shelf-life, quality and safety aspects. Combining the process of emerging non-thermal and other eco-friendly techniques such as high-pressure processing, ultrasound, irradiation, ozone treatment, phage therapy etc., with bioactive food packaging seemed to be a promising sustainable alternative to improve shelf-life, quality and safety of the crab meat and derived products.

Solid and liquid wastes from crab processing contain many biomolecules such as pigments, proteins, chitin, flavour compounds, and peptides that have enormous application in almost every fields of science. Different innovative methods and processes such as ionic liquid extraction, subcritical water pre-treatment, hybrid plasma, and hot water−carbonic acid process are now used for a better yield of chitin and its derivatives from crab-shells. Further, green extraction of bioactive components using natural deep eutectic solvents in combination with appropriate technologies like subcritical and supercritical extractions; microwave assisted extraction, ultra-filtration etc. for maximum recovery of active biomolecules. Again, the concept of shell biorefinery via microbial fermentation or through catalytic approaches for valorisation or biotransformation of chitin biomass into valuable nitrogen containing chemicals and other materials is gaining popularity. These aforementioned processes are convenient, environment-friendly and sustainable over conventional methods, and could easily be explored for large-scale applications.

In summary, there is great scope to transform the waste/ biomass generated from crab processing into novel biobased products, which in turn would help in reducing the pressure on the environment and landfill/disposal problems. By recycling and reusing these wastes in foods, feed, pharmaceuticals, and other industries, the blue bioeconomy would certainly help the crab industry in moving towards a more circular economy having a global sustainable future.

Conflict of interest

The authors declare that there are no conflicts of interest.

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Table 1. Chemical and fatty acids composition (SFA, MUFA and PUFA) of important edible crabs

Crab species	**Moisture (%)**	**Protein (%)**	**Fat (%)**	**Ash (%)**	**Fatty acids** (%)	**References**
Chinses mitten crab (*Eriocheir sinensis*) meat (grade-I)	79.2	18.2	0.8	-	SFA=17.5; MUFA=24.8; PUFA=50.6 n3PUFA=30.6, DHA=13.4; EPA=14.9	Wang et al. (2018)
Mud crab (*Scylla serrata*) meat (natural)	83.6	22.8	1.35	2.1	*SFA= 23.3; MUFA= 25.8; PUFA= 42.9; n3PUFA= 40.0; EPA= 15.5; DHA= 11.8	Sarower et al. (2013) Anas et al. (2010)*
Mud crab (*S. serrata*) meat (fattened)	81.0	27.4	1.9	3.5	*SFA= 23.7; MUFA= 23.9; PUFA= 42.2; n3PUFA= 39.3; EPA= 14.6; DHA= 11.1	
Blue crab (*Callinectes sapidus*) body meat (female)	67.5	26.5	1.6	1.2	SFA=25.9; MUFA=22.0; PUFA=41.1	Kuley et al. (2008)
Common mangrove crab (*Sesarma brockii*) meat	43.7	26.1	3.2	16.5	SFA=49.3, MUFA=9.4; PUFA=39.4	Sakthivel et al. (2014)
Swimming crab (*Portunus sanguinolentus*) meat	79.4	28.4	8.8	12.3	EPA=13.4; DHA= 11.9	Wilson et al. (2017)
Long-eyed swimming crab (*Podophthalmus vigil*)	75.0	21.5	0.3	0.3	-	Soundarapandian et al. (2013)
Box crab (*Calappa lophus*) body meat	73.1	21.5	1.3	2.56	-	Kathirvel et al. (2014)
Blue crab (*C. sapidus*) claw meat	78.0	19.5	0.4	2.13	#EPA=10.6; DHA=5.9, n3PUFA=18.1	Küçükgülmez et al. (2006) Çelik et al. (2004)#
Blue crab (*C. sapidus*) breast meat	79.1	18.8	0.4	2.0	#EPA=8.4; DHA=6.8, n3PUFA=17.0	
Mud crab (*Scylla tranquebarica*) body meat- male	81.5	15.6	0.7	1.6	SFA=48.0; MUFA=17.0; PUFA=32.1, n3PUFA=22.5	Sreelakshmi et al. (2016)
Mud crab (*S. tranquebarica*) body meat- female	78.6	17.6	1.2	2.0	SFA=46.0; MUFA=21.1; PUFA=30.3, n3PUFA=19.2	
Blue swimmer crab (*Portunus pelagicus*) meat- male	79.5	16.9	0.8	-	SFA=25.4; MUFA=23.4, PUFA=42.1; n3PUFA=29.9	Wu et al. (2010)
Blue swimmer crab (*P. pelagicus*) meat- female	78.2	18.4	1.1	-	SFA=26.2; MUFA=26.4, PUFA=39.4; n3PUFA=28.3	
Deep-sea red crab (*Chaceon maritae*) meat-female	76.6	17.7	1.0	3.2	SFA=21.1; MUFA=25.7; PUFA=46.9; n3PUFA=39.0	Mandume et al. (2019)
Brown crab (*Cancer pagurus*)	77.8	16.4	0.2	2.1	SFA=17.4; MUFA=30.8; PUFA=48.4;	Barrento et al. (2010)

meat-female					n3PUFA=36.6	
Brown crab (*C. pagurus*) meat-male	74.6	20.5	0.2	1.9	SFA=16.7; MUFA=30.9; PUFA=48.9; n3PUFA=35.8	
Atlantic spider crab (*Maja brachydactyla*) meat -female	79.2	15.7	0.3	2.5	SFA=20.8; MUFA=22.7; PUFA=52.2; n3PUFA=42.0	Marques et al. (2010)
Southern king crab (*Lithodes santolla*) meat-male	80.9	14.6	0.7	2.1	SFA=23.7; MUFA=29.1; PUFA=38.6; n3PUFA=29.7	Risso & Carelli (2012)
Swimming crab (*Portunus trituberculatus*) meat-female	78.3	15.7	1.2	-	SFA=21.8; MUFA=34.4; PUFA=43.5; n3PUFA=36.9	He et al. (2017)
Green crab (*Carcinus mediterraneus*) claw meat	80.0	18.0	1.0	-	SFA=23.0; MUFA=23.2; PUFA=37.3; n3PUFA=22.3	Cherif et al. (2008)
Green crab (*C. maenas*) whole meat	67.9	12.3	0.21	16.6	SFA=23.3; UFA=67.9; n3PUFA=18.9; EPA=8.7; DHA=7.7	Fulton & Fairchild (2013)
Orange mud crab (*S. olivacea*) meat-female	60.0	13.3	0.2	-	+SFA=49.6; MUFA=37.8; PUFA=12.6; n3PUFA=7.8	Wan Yusof et al. (2019) Azra et al. (2020) +
Freshwater crab (*Potamon potamios*) meat -female	78.9	13.9	0.7	1.5	-	Bilgin & Fidanbaş (2011)
Indian ocean swimming crab (*Charybdis smithii*) meat-male	86.9	9.48	0.9	0.4	SFA=51.3; MUFA=25.46; PUFA=23.2; EPA=10.4; DHA=9.2	Yogesh Kumar et al. (2019)
Southern king crab (*Lithodes santolla*) meat- male	80.9	14.6	0.7	2.03	SFA=23.7; MUFA=29.1; PUFA=38.8; n3PUFA=29.7; EPA=17.1, DHA=11.0	Risso & Carelli (2012)
Soldier crab (*Mictyris brevidactylus*)	74.8	11.4	1.1	9.4	SFA=33.6; MUFA=19.0; PUFA=35.9; n3PUFA=27.1; EPA=11.7, DHA=13.7	Liu & Chen (2020)

DHA: Decosahexaenoic acid; EPA: Eicosapentaenoic acid; MUFA: Monounsaturated fatty acid; PUFA: Polyunsaturated fatty acid; SFA: Saturated fatty acid

Table 2. Effects of different traditional and innovative preservation technologies on quality, safety, and shelf-life of crab meat

Crab source	Processing method, conditions, duration and temperature	Quality changes	References
Blue crab (*Callinectes sapidus*)	HPP (100, 300 or 600 MPa/5 min) effect on the gelling capacity of blue crab meat	• HPP at 100 and 300 MPa increased the gelling capacity and improved the texture, brightness and appearance • Crab meat gels had a lighter and reddish colour in HPP treated samples	Martínez-Maldonado et al. (2020)
Mud crab (*Scylla serrata)*	Effect of gamma radiation (0.5, 1.0 or 2.0 kGy) on muscle tissues of crab at cellular and nuclear level	• Gamma radiation at 2.0 kGy reduced sarcomere length, ruptured sarcotubular system, mitochondrial swelling and nuclear damage • Precise irradiation dose was 1.0 kGy	Keethadath et al. (2019)
Crab (*Ovalipes punctatus*) meat	Effect of electron beam irradiation (EBI) at doses of 1.0, 3.0, 5.0, 7.0 or 9.0 kGy	• Smell of crab meat could be maintained at ≤5 kGy doses, but resulted in slight off-odour at ≥7 kGy • EBI had effect on sensory scores which decreased with the increase in dose. • The number of volatile flavour compounds (55) in crab meat increased to 60, 57, 62, 60 and 58 after irradiation at 1, 3, 5, 7, and 9 kGy, respectively. • No impact on the key volatile flavour compounds.	Mei et al. (2018)
Cooked snow crab (*Chionoecetes opilio*) clusters	Effect of freezing conditions (brine, still air, and circulating air), frozen storage times (72 h and 6 months), and thawing methods (air and circulating water) on physico-chemical changes of stored (-20 °C) cooked snow crab clusters	• Both freezing methods and storage times affected the weight changes and drip loss in clusters • Freezing in brine or thawing in air minimized weight loss • Clusters frozen in brine and thawed in water minimized melanosis	Lorentzen et al. (2020)
Swimming crab (*Portunus trituberculatus)*	Effects of super-chilling and MAP-60% CO_2 on the quality and shelf-life of meat stored at-3 ± 1°C	• Both treatments extended the shelf-life of crab meat to 15–20 days • MAP with 100 % CO_2 had a negative effect on the drip loss and overall acceptability of meat	Sun et al. (2017)
Edible estuarine crab (*S. serrata*)	Combined effect of dose-dependent gamma irradiation (0.5, 1.0 or 2.0 kGy) and storage temperature (4 °C or	• Gamma irradiation (≥1.0 kGy) and frozen storage (-20° C) extended shelf-life of crab meat for 28 days maintaining good sensory quality	Arshad et al. (2015)

	-20°C) on sensory characteristics of crab meat vacuum packed in pre-sterilized polyethylene bags and studied up to 28 days	• Irradiation of frozen stored crab meat at any dosage had no significant advantage on sensory characteristics up to 14 days compared to controls	
Crab meat (*Portunus pelagicus*)	Effect of seasoning with herb leaves-rosemary, oregano and laurel (0.6 %) on the quality of precooked (83°C for 10 min) and vacuumed crab meat stored at 4°C for 57 days	• Seasonings delayed spoilage and improved the sensory quality of precooked and vacuumed crab • Samples treated with herb leaves had better shelf-life (40-42 days) than controls (38-40 days)	Ayas et al. (2012)
Cooked edible crab (*Cancer pagurus*)	Quality attributes and shelf-life of cooked and vacuum-packed meat stored at 4°C for 3 months	• Live refrigerated crab meat exhibited better shelf-life (> 13 days) in comparison to live frozen and dead refrigerated (between 4-10 days).	Anacleto et al. (2011)
Bloated crab (*P. trituberculatus*)	Effect of frozen (-18℃) and refrigerated (4℃) storage conditions on sensory quality and chemical changes of crab meat	• Sensory quality of bloated crabs exceeded acceptable limits under 4℃ and-18℃ on 10th day and 6th month, respectively • TVC value of refrigerated samples increased remarkably compared to frozen storage conditions but was < 5 log (CFU/g) until 16th day • TVB-N value of the meat samples exceeded the first-order freshness range under storage conditions of 4℃ and -18℃ on 12th day and 6th month, respectively.	Qian et al. (2019)
Crab (*C. pagurus*) meat (White and brown)	Effect of chemical treatment- lactic acid, sodium chloride, acetic acid, or citric acid at 5% on microbial spoilage and shelf-life of crab meat stored at 2°C for 12 days	• Acetic acid was effective in extending shelf life of white meat to 8-11.5 days against 5 days in case of untreated control samples. • Acetic acid treated samples had comparatively lower bacteria growth. • Shelf-life of crab meat extended by up to 3 days using lactic acid whereas it was more than doubled by acetic acid	McDermott et al. (2018)
Red snow crab (*Chionoecetes japonicus*)	Changes in quality of frozen crab leg meat stored at -20 °C for 7 weeks	• Discoloration around carapace noticed at 2-week whereas the leg muscle turned yellow at 3-week	Jun et al. (2017)
Cooked blue swimming crab (*P. pelagicus*) meat	Shelf-life extension of refrigerated crab meat dip treated for 2 min in sodium acetate at 1.0, 1.5 or 2.0%	• Meat dipped in 2.0% sodium acetate had better shelf-life (12 days) compared to 6 days in control	Lohalaksanadech & Sujarit (2011)
Crucifix crab (*Charybdis*	Biochemical, microbiological and	• TVB-N and TMA-N values were within an	Anupama et al. (2018)

feriatus)	sensory parameters of whole crab stored under refrigerated conditions (at 4°C) for 8 days	acceptable limit up to 6 days of storage but increased thereafter • Concentration of cadaverine increased and psychotropic and mesophilic bacterial count exceeded the permissible level of acceptance beyond 6 days of storage.	
Mud crab (*S. serrata*)	Effect of non-thermal processing (high pressures 345 MPa for 5 min) on physical characteristics of crab meat	• Separation of crab meat from the shell easier through application of HPP compared to control • HPP treatment provided freshness, cook appearance, microbial safety and hard texture to the treated products	Mohamed et al. (2015)
Crab paste	Evaluation of quality and safety aspects through antibacterial and natural chemical treatment of crab paste stored under frozen conditions at −20°C	• Combined (antibacterial and natural chemicals) treatment had synergistic effects and effectively inhibited the increasing values of TVC, pH, and TVB-N as compared to control • Combined treatment was effective in reducing foodborne pathogens, inhibited microbial spoilage, and maintained the quality and safety of crab paste under frozen storage conditions.	Luo et al. (2020)
Edible crab (*C. pagurus*)	Ultrasound in combination with temperature (50°-80 ºC) to reduce cadmium (Cd) content in meat	• Ultrasound increased Cd release rates- 8.7, 2.1 or 2.7-fold in conjunction with the treatments at 50, 65 or 80 °C, respectively. • Ultrasound could serve as an effective physical procedure for reducing the Cd content of crabs in processing industry	Condón-Abanto et al. (2018)
Blue crab meat (*C. sapidus*)	Effect of HPP at 100, 300 or 600 MPa (10 °C/5 min) on the muscular protein fractions and yield of crab meat compared to thermal cooking process (90 °C/20 min)	• Increasing in pressure level resulted in a decrease in denaturation of myofibrillar protein fractions • HPP at 100 and 300 MPa resulted in a significant increase in the yielding of meat extracted • Higher HPP (300 and 600 MPa) improved the sensory scores resulting in better acceptance.	Martínez et al. (2017)

CFU: Colony forming unit; CO_2: Carbon dioxide; HPP: High pressure processing; kGy: Kilo gray; MAP: modified atmosphere packaging; MPa: Megapascal; TMA-N: Trimethylamine- nitrogen; TVC: Total viable count; TVB-N: Total volatile base-nitrogen

Table 3. Quality attributes of crab meat based novel value-added food products**.**

Crab meat- based product	Parameters studied	Effects	References
Empanada or pastelitos South American stuffed and fried pastry containing green crab, *Carcinus maenas* mince at 30, 50 or 70 %	Sensory parameters and acceptability	• Empanadas with 30 or 50 % mince had better attributes in terms of filling appearance, flavor and overall liking as compared with 70 % mince	Galetti et al. (2017)
Seafood-flavoured snacks Atlantic rock crab processing by-product (0%–40%) blended with corn meal and potato flake	Storage study for 3 months at room temperature	• Crab processing by-product and additives had positive effect on pH, bulk density, and improved calcium content • Development of a calcium rich seafood-flavoured snack	Murphy et al. (2003)
Crab meat patties Green crab, *C. maenas* meat mince cooked with 5 % soy protein isolate with or without 1, 2 or 4 % transglutaminase	Physic-chemical parameters, and textural profile analysis	• Crab mince meat patties had increased cook yield, improved gel strength, and water-holding capacity • Increasing levels of transglutaminase decreased the moisture content, gumminess, hardness, springiness, and chewiness of the patties • Soy protein isolate at 5 % in combination with transglutaminase (2 %) was the most acceptable	(Galetti, 2010)
Ready-to-serve bread spread Blue swimmer crab, *Portunus pelagicus* meat	Chemical, physical and sensory quality at process temperatures (115, 121.1, or 130 °C) to an F_0 value of 6 min	• Least increase in trimethylamine- nitrogen and total volatile base-nitrogen values at 130°C whereas least increase in free fatty acid value at 121.1°C • Thermal processing at higher temperature increased the loss of amino acids and affected the colour values • Product processed at 121.1 °C rated with better sensory scores compared to 115 and 130 °C	Biji et al. (2013)
Crab meat pasta Underutilized meat mince from the carapace and legs of Jonah crab, *Cancer borealis* at 10 or 20% level with additives and or red colorant	Sensory and quality analyses	• Pasta had a slight seafood flavour and a gritty texture because of residual shell particulates • Pasta containing red colorant and 10% crab mince had significantly lower colour; however with no differences in flavour, texture, aroma, or overall acceptability	(Gillman, 2001)
Restructured crab meat product Meat from Jonah crab, *C. borealis* with dried egg whites	Sensory and quality analyses	• Product with dried egg whites had increased hardness, cohesiveness, springiness and gumminess	(Baxter, 2007)
Crab appetizers Cross between a crab cake and a nugget: Italian, Jalapeno, or Curry	Consumer acceptability	• The Italian appetizer scored better for all the tested attributes compared to the Curry and Jalapeno varieties	(Baxter, 2007)

types with dry egg white at 4.0%			
Crab powder in fish paste Leg-meat powder at 3, 6, 9 or 12% of Red snow crab, *Chionoecetes japonicus* in fish paste	Quality characteristics and sensory evaluation	• Decreased *L** value and increased *a** and *b** values observed with increased crab meat powder concentration • 6% powder concentration had better sensory scores in terms of hardness, springiness, and gumminess	Kim et al. (2016a)
Ready-to-serve crab sandwich spread Meat of mud crab, *Scylla serrata*	Different combinations of temperature and F_0 value (three variables of temperature- 121.1°C, 116.1°C, or 111.1° and F_0 value at 5, 6, or 7 min, respectively) on texture, colour, and sensory attributes	• Product processed at higher temperature (121.1 °C and F07 min) had better flavour and overall acceptability scores • Different time and temperature combinations had no significant effect on colour, odour, taste, and spreadability of the spreads	Sreelakshmi et al. (2015)
Ready-to-eat crab koftha or fried crab balls Meat of *P. pelagicus*	Sensory, instrumental texture and colour analysis of crab balls (Thermal processing at three different F_0 values- 5, 6 or 7 at 121.1°C)	• Crab koftha when processed to $F_0$6 had desirable texture and received very good acceptability scores than products processed to $F_0$5 and $F_0$7	Abhilash et al. (2013)
Noodles Lyophilized leg-meat powder @ 2, 4, 6, 8 or 10% level of red snow crab, *C. japonicus*	Quality characteristics and sensory attributes	• High meat powder concentration increased the ash, crude protein and crude lipid contents of noodles • The *a** and *b** values increased whereas *L** values of the noodles decreased with increasing powder content • Cooked noodles with 4 – 6 % meat powder had greater overall acceptability	Kim et al. (2016b)
Crab paste patties Red-tanner crab, *C. japonicus* paste at 5, 10, 15, 20, 25 or 30 % level	Chemical characteristics and sensory evaluation	• Increasing the level of crab paste reduced moisture (64.8 to 61.5 %) but increased the ash contents (2.3 to 3.7 %) of patties • Sensory scores on colour and flavour increased whereas the texture score decreased with increasing paste level • Patty with 15 % crab paste had better physical properties and sensory reports.	Heu et al. (2005)
Crab stock concentrate Cooking water of blue swimmer crab, *P. pelagicus* blended with herb flavor or chilli tomato	Evaluation and sensory analysis of boiled, vacuum or freeze-dried crab stock concentrate	• Crab stock concentrate produced using vacuum dryer was the most acceptable • Tomato crab stock was the most preferred with high acceptability ratings and resembled more soup-like	(Choo, 2009)

		characteristics	
Crab cakes By-product of blue crab in various combinations of claw mince/meat, functional soy protein concentrate-SPC at 30, 40 or 50% level and surimi	Sensory, quantitative and qualitative characteristics	• Crabby flavour decreased and beany flavour increased when claw mince was increased in the formulation • Cakes with 50% SPC had lower scores for firmness than those with lower SPC levels • SPC at any level has no effect on the cohesiveness scores	Lee et al. (1993)

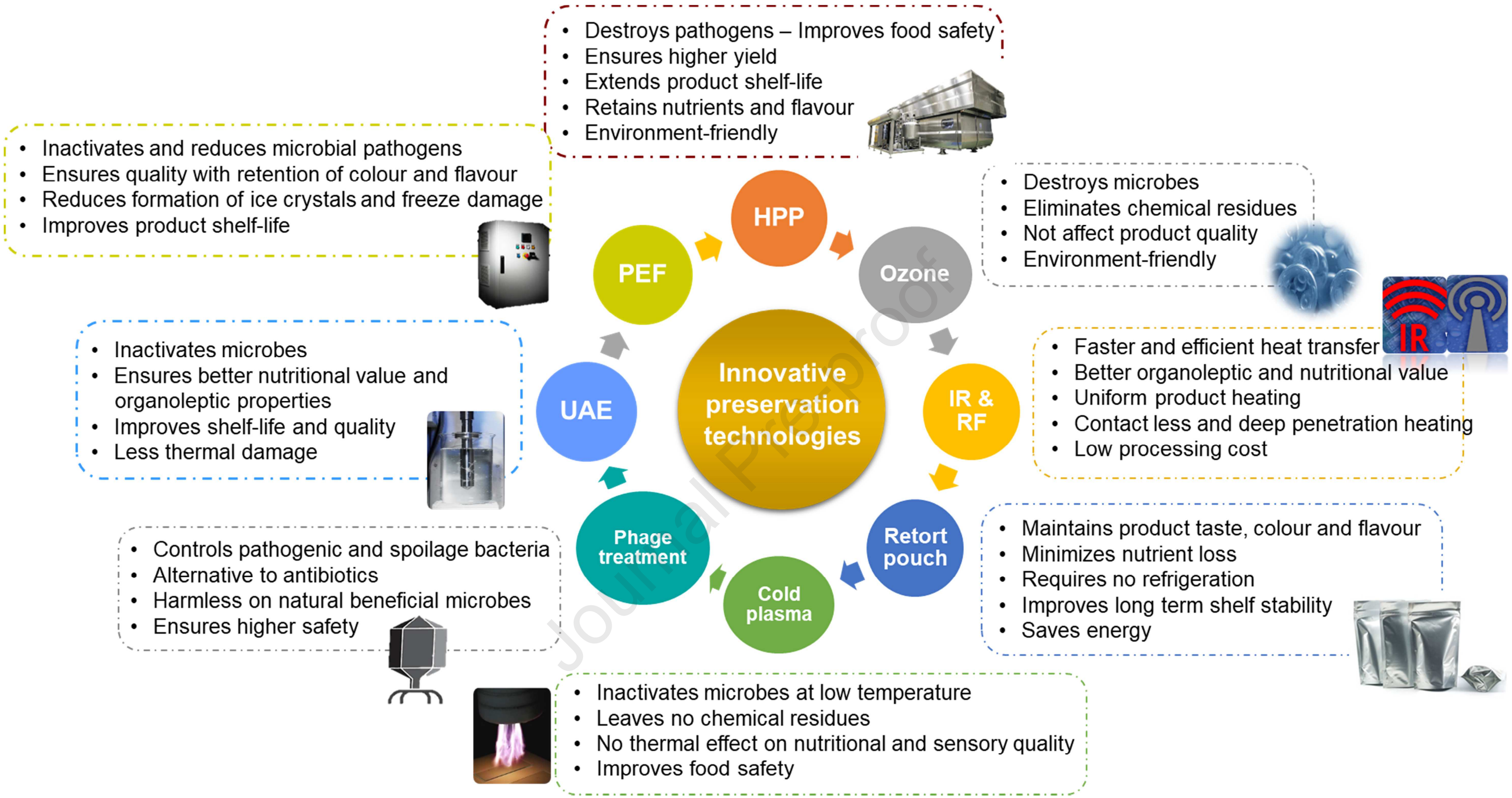

Fig 1. Different innovative preservation technologies for quality, safety and shelf life of crab meat.

(HPP-High pressure processing, PEF=Pulsed electric field, IR &RF=Infra-red and radio-frequency, UAE-Ultrasound assisted extraction)

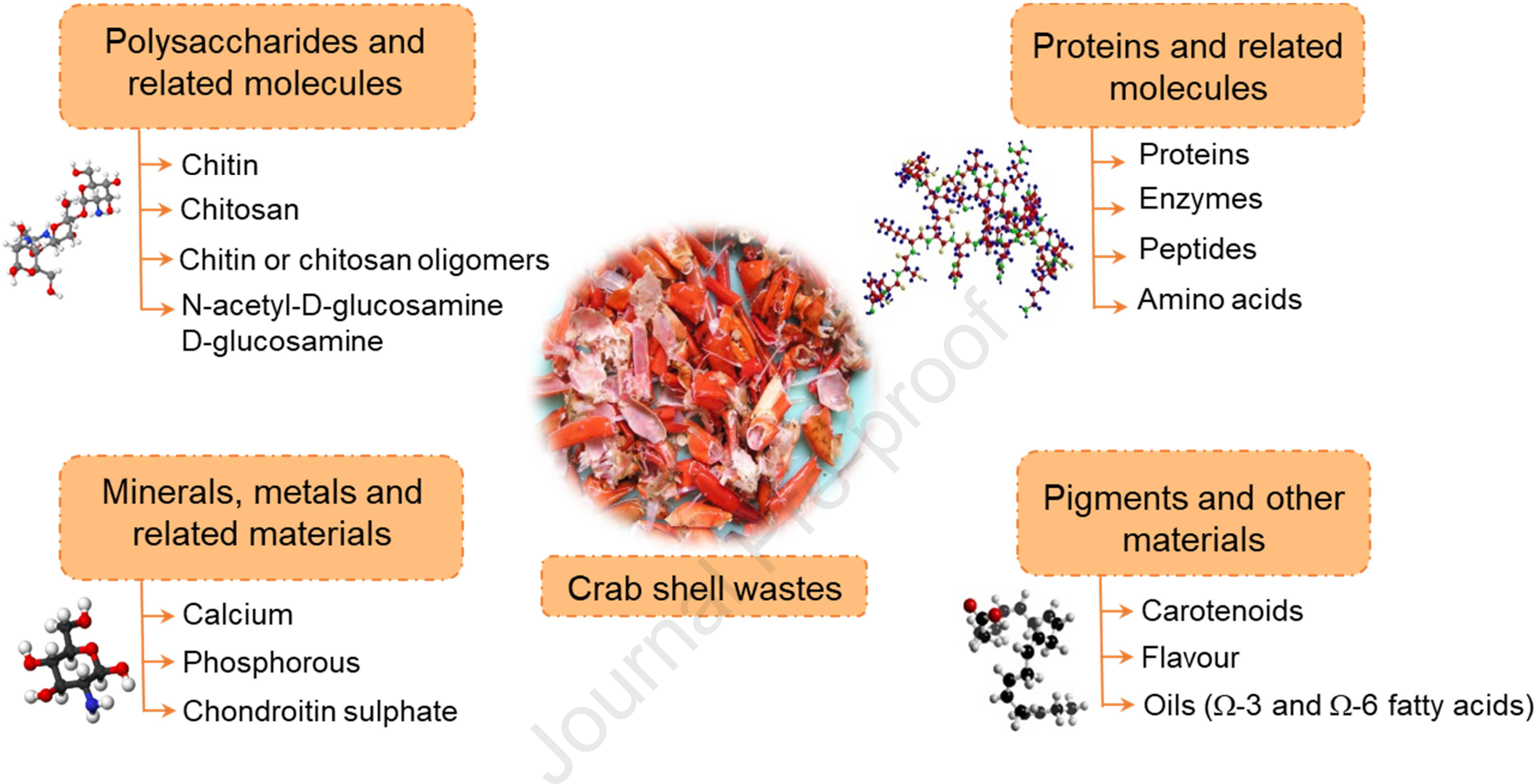

Fig 2. Different functional and nutritional components from crab shell wastes.

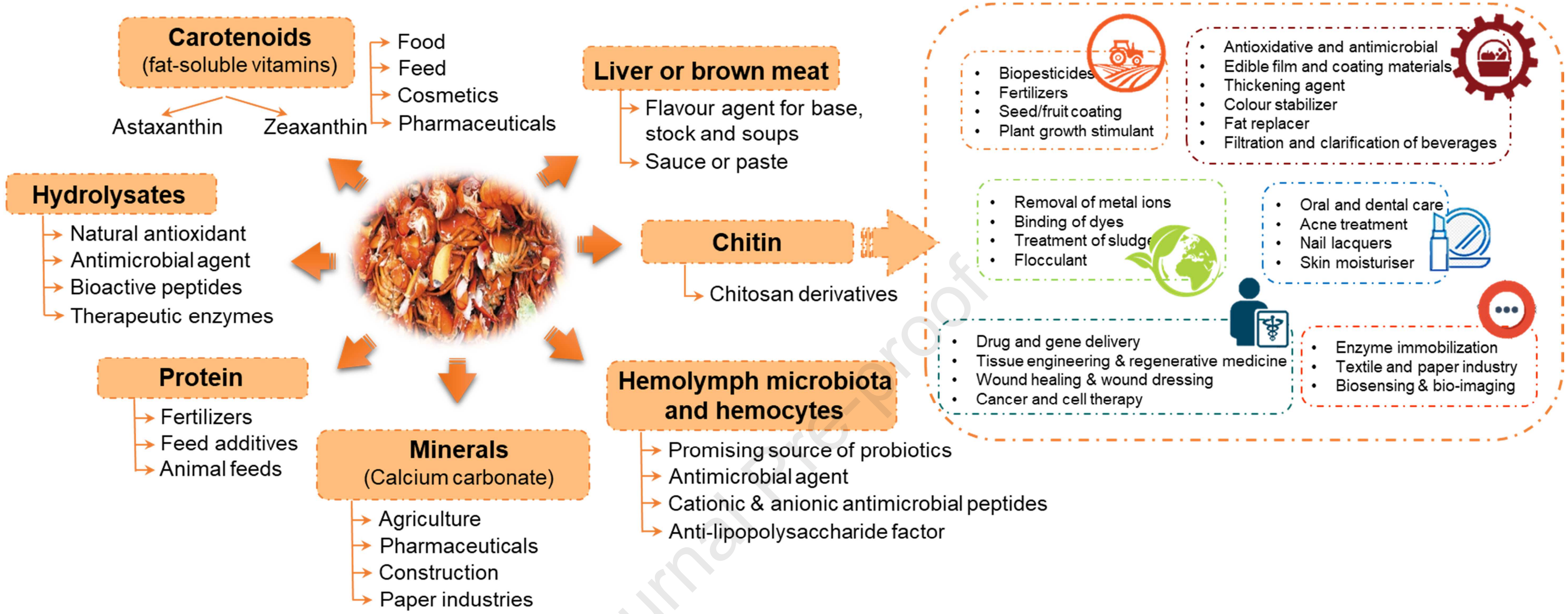

Fig 3. Valorised products from crab processing wastes and their application in different fields.

Highlights

- First report covering nutritive value and flavour profile, health benefits of crab meat, and acceptability of novel value added crab meat based processed products
- Crab meat is quite popular for its unique flavour and delicious taste.
- Crab meat is an excellent source of important nutrients
- Crab meat have great potential as quality and healthy food
- Applications of valuable products derived from valorisation of crab processing bio-products