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**Microbiological and Physico-Chemical Safety Assessment of Dried Blue
Crab (*Callinectes sapidus*): Ensuring Safety and Traceability in the Blue
Crab Valorization Chain**

Supervisor: Prof. Marta Castrica

Student: Lara Mina Kutlar

Student ID: 2106134

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Abstract

Blue crab (*Callinectes sapidus*) is an invasive species that is rapidly spreading in new habitats such as the Mediterranean and the Adriatic, causing serious ecological and economic problems. In this study, the microbiological and physical-chemical safety of drying invasive blue crab biomass for food/feed purposes was investigated. The W15 drying technology was used to prepare blue crab samples from Scardovari Lagoon in Italy in order to produce a uniform and stable end product. The product undergone extensive analysis: The absence of the primary pathogens, including *Vibrio parahaemolyticus*, *Staphylococcus* enterotoxins, and *Clostridium* that produces botulinum toxin, was verified by microbiological testing. According to heavy metal assessments, the product consists of around 2.41 mg/kg of lead (along with 0.28 mg/kg of cadmium and 0.079 mg/kg of mercury); these levels, compared to some legal limitations, indicate that lead levels in particular need to be regularly checked. Based on microplastic tests, there was a small amount microplastic in the product, and there is a low risk to human health at this level. The nutritional profile analysis showed that the dried blue crab product has a high protein content (34.3%) and ash content (41.1%), but a low moisture content (6.44%) and fat content (3.93%). While the high protein level indicates that the product can be used as an alternative protein source, such as pet food or aquaculture feed, the high ash content indicates that minerals, such as calcium and magnesium, from the crab's skeleton and tissues are concentrated in the product. Furthermore, it has been observed that the product is high in a number of minerals, such as calcium, and B vitamins, including pantothenic acid (B5), B1, niacin (B3), and B12. According to the study, the invasive blue crab may be dried and converted into a wholesome product, making it a viable source for the food and feed industries. However, regular control and strict monitoring of heavy metal contents are

recommended in order to ensure the safety and traceability of the product. With this approach, the invasive blue crab can be transformed from an environmental problem into a value-added resource within the scope of the circular economy. To ensure the safety and traceability of the product, it is suggested that heavy metal contents be strictly monitored and controlled on a regular basis. In the context of the circular economy, this strategy can turn the invasive blue crab from an environmental issue into a resource with added value.

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1. Introduction

Innovative study into the exploitation of marine resources has been started by the growing demand for sustainable food sources worldwide and the successful control of invasive species. The blue crab (*Callinectes sapidus*), which is highly valuable in its natural habitat but is a problem in the Mediterranean and Adriatic Seas and many other areas, is highlighted in this study. The uncontrolled spread of *C. sapidus* causes several significant economic and ecological problems such as habitat destruction, biodiversity loss, and financial losses to nearby fisheries. The food technology sector is trying to find new ways to transform *C. sapidus* into value-added products in order to minimize the problems that occur while optimizing its economic potential. One promising approach is to convert blue crab biomass into pet food ingredients. This strategy offers an alternative protein source to the pet food industry and contributes significantly to the sustainable management of the *C. sapidus* population. By reusing blue crab waste and by-products, this plan reduces its negative impact on the environment and opens up novel business prospects for the fishing and food processing industries. Examining the viability of turning blue crabs into an acceptable food source for pet food production is the goal of this study. Blue crabs' biological traits, economic significance, and sustainable use practices are highlighted. Using Italy's Scardovari Lagoon as an example, this study also highlights how the expanding blue crab population threatens the balance of the ecology and indigenous aquaculture. Using an interdisciplinary approach that blends environmental management, food technology, and marine biology, this study attempts to offer workable answers for viewing blue crabs as a beneficial resource rather than a dangerous invading species.

1.1. Blue Crab (*Callinectes sapidus* Rathbun)

The blue crab (*Callinectes sapidus* Rathbun, 1896 (Brachyura: Portunidae)), which is native to the western Atlantic Ocean (Kevrekidis et al., 2023), is an opportunistic euryhaline species that

lives in brackish and marine habitats such as estuaries, lagoons, and other coastal habitats (Mancinelli, Bardelli, & Zenetos, 2021; Taybi & Mabrouki, 2020).

Blue crabs spend the most of their life cycle in estuaries, where they are distributed according to temperature, salinity, and dissolved oxygen (Kevrekidis et al., 2023). This species' life cycle is heavily influenced by temperature. Blue crabs can tolerate temperatures ranging from 0 to 39 °C, depending on their ability to adjust to temperature and salinity (Kevrekidis et al., 2023; Tagatz, 1969). During the warm season, eggs are produced and incubated, but feeding, movement, and moulting stop when temperatures drop below 10 °C (Hines et al., 2010). Blue crabs complete their life cycle under a variety of salinity regimes. For instance, they use low-salinity conditions for mating and nursery habitats, as well as saltwater salinity levels for larval development (Marchessaux et al., 2022). As a result, blue crabs may survive and thrive in a variety of salinities (Kevrekidis et al., 2023). Furthermore, blue crabs move along a salinity gradient based on sex and life stage: males and juveniles favor oligohaline waters upstream, whereas adult females prefer meso- and polyhaline salinities (Taylor & Fehon, 2021). Dissolved oxygen has been shown to have a major impact on blue crab development and abundance. Dissolved oxygen levels below 2-4 mg/L were found to trigger an avoidance reaction in crabs, and levels below 1.2 mg/L resulted in mortality (Taylor & Fehon, 2021). The successful dissemination of blue crabs across various geographical regions can be attributed to their intrinsic biological traits: rapid growth rate, opportunistic feeding (on vegetation, detritus, polychaetes, molluscs, crustaceans and fish), high rate of reproduction, versatile habitat utilization, extensive larval dispersal capacity, and proficient physical and aggressive behaviours, which includes scavenging and cannibalism (Kevrekidis et al., 2023; Mancinelli et al., 2017; Kampouris, Porter, & Sanderson, 2019). Owing to these attributes, the blue crab, which was inadvertently introduced in the early 20th century into the Mediterranean Sea, likely via ballast water (Nehring, 2011), and was intentionally introduced into the Aegean Sea during the 1930s (Zotti et al., 2016), has since proliferated extensively throughout the Mediterranean,

the Black Sea, and the European coastlines of the Atlantic Ocean (Mancinelli, Bardelli, & Zenetos, 2021). Thus far, blue crabs are classified among the top one hundred “most detrimental” invasive alien marine species in the Mediterranean Sea, exerting a significant influence on ecosystem biodiversity and anthropogenic activities (including fisheries, aquaculture, and tourism) (Piras, Esposito, & Meloni, 2019; Khamassi et al., 2022). This species possesses the capacity to instigate profound alterations in the composition and structural integrity of marine communities within coastal zones by competing with indigenous species for essential resources (Kevrekidis et al., 2023; Clavero et al., 2022). It exerts a detrimental effect on artisanal fisheries, diminishing both the quantity and quality of catches, while adversely impacting overall revenue (Ravera, 2000). Despite the adverse consequences, the blue crab may be regarded as a novel source of income, given its substantial nutritional value (Mancinelli et al., 2017; Ravera, 2000; Khamassi et al., 2022; D’Alpaos, 2010); its exploitation could enhance the economic conditions of both the local fishing and processing sectors through its integration into local industries and the valorization of by-products (Mancinelli et al., 2017; Khamassi et al., 2022).

2. The Economic Role of Blue Crab and Sustainable Practices

In recent decades, rapid globalization and increased travel, trade, and transportation have hastened the introduction of alien species. Invasive alien species (IASs) can cause significant damage to native species and ecosystems, as well as economic and health implications (Pyšek et al., 2020; IUCN, 2000). Invasive alien species are one of the five most direct drivers of biodiversity loss, alongside changes in land and sea usage, direct exploitation of species, climate change, and pollution. More than 3500 species are invasive worldwide, with verified impacts on the marine environment accounting for 10% (IPBES, 2023). Even while invading alien species offer a severe worldwide hazard, they are frequently underestimated and unacknowledged (Castriota et al., 2024).

The Atlantic blue crab *Callinectes sapidus* Rathbun, 1896 (Brachyura: Portunidae) is found along the western Atlantic coast, from Nova Scotia in Canada to northern Argentina, and includes Bermuda and the Antilles (Williams, 1974). It has been named one of the 100 most invasive alien species in the Mediterranean Sea (Streftaris & Zenetos, 2006) and is generating a lot of attention due to its rapid colonization of new fields, significant population growth, and potential impacts on ecosystems and services. It was recently discovered in a western Mediterranean area that *C. sapidus* invasion has the potential to cause major alterations in the structure and composition of coastal marine and freshwater populations, with direct implications for biodiversity protection and coastal human population survival (Clavero et al., 2022). On the contrary, the species is a valuable resource in its natural habitat and is beginning to be recognized in some Mediterranean fisheries (Mancinelli et al., 2017; Kevrekidis et al., 2023).

Callinectes sapidus has invaded a significant portion of the Mediterranean Basin and its surrounding waterways, as well as Northwest Europe. In some regions, it has demonstrated an invasive nature (Clavero et al., 2022; Kevrekidis et al., 2023; Oussellam et al., 2021) that has resulted in a severe socioeconomic impact (Oussellam et al., 2021) and necessitated immediate action to restrict the population (Castriota et al., 2024).

2.1. Economic Value of Blue Crab

Crabs are among the organisms that command high prices in Western countries for their edible meat quality and economic importance. Blue crab (*Callinectes sapidus* Rathbun, 1896) is one of the most important crab species fished for commercial purposes worldwide (Kocatepe et al., 2013).

The crab industry has become established in industrialized countries. In this industry, crabs are processed multiple times before being packaged into three categories of products: crab meat, whole crabs, and crab byproducts. Waste includes shells, chitin, protein concentrations, residual

meat, and offal. Among these, the high-protein and mineral-rich leftover meat is fed to cattle, pigs, poultry, and fish (Paul & Haefner, 1985).

Callinectes sapidus supports a significant fishery in both its natural range along the Atlantic coast of North America and its introduced area in the eastern Mediterranean Sea. However, due to climate change and its alleged favorable impacts on the occurrence of blue crabs, *C. sapidus* may well become a target species in commercial fisheries elsewhere. This might be an actual scenario in the Adriatic Sea, along the European Atlantic coast, or in the North Sea. Otherwise, it will be interesting to see if *C. sapidus* will dramatically decrease stocks of the established Pacific oyster (*Crassostrea gigas*), which is commercially used in several European countries because grown-up blue crabs prefer molluscs like oysters as their main source of nourishment (Hill et al., 1989). Blue crabs are said to mutilate fish collected in traps and trammel nets, tearing those nets (Banoub, 1963; Beqiraj & Kashta, 2010).

It is now widely recognized that the only method to control this invasion is to fish for and use blue crabs as a resource, and that total elimination of blue crabs is currently an impractical goal (Marchessaux et al., 2023). In reality, blue crab fisheries continue to rank among the highest-value commercial endeavors in their home locations, particularly in the United States and Mexico (Allen et al., 2023; Perry et al., 2022). Because of its distinct flavor and taste, as well as its nutritional value as a source of high-quality proteins, unsaturated fatty acids, vitamins, minerals, and a number of bioactive substances, crab flesh is a popular food (Nanda et al., 2021). These qualities allow crab by-products to be utilized as raw materials for a variety of crab-based products, as well as food additives and flavor enhancers (Obatolu et al., 2005).

Furthermore, up to 85% of the crab's live weight is made up of food-grade residues and by-products (such as shells, legs, guts, and meat residues) (Chung & Cadwallader, 1993) produced by the crab processing industry. Around 270,000 tons of post-processing trash are produced by blue crab fisheries worldwide, assuming an average hand-picked meat yield of 100 g/kg (FAO Fisheries and Aquaculture Department, 2022). This is particularly troublesome in nations

without a recovery/valorization supply chain, where this kind of trash is frequently burned or dumped in landfills (Rudovica et al., 2021). As a result, environmental awareness and laws have promoted alternatives for the exploitation and valorization of crab waste (Vidal et al., 2022). Blue crab waste can once again be used for animal feed, the extraction of bioactive chemicals, carbonaceous material, and biofiller (Tamburini, 2024).

2.2. Ecological and Economic Impacts of Blue Crab

Over 60 years after the repercussions of accidental species introductions were first officially acknowledged (Elton, 2020), addressing the adverse effects of invasive alien species (especially invasive alien fauna) continues to be a significant conservation challenge (Carlton, 1996; Bright, 1999; Occhipinti-Ambrogi, 2007). Biological invasions pose a global threat to the structure and function of aquatic ecosystems, leading to significant biodiversity losses and disruptions in habitat functioning worldwide (Molnar et al., 2008). Addressing the consequences of invasions poses significant challenges in aquatic environments due to the fact that the pace of invader establishment often greatly surpasses the available resources for their management (Mooney & Cleland, 2001; Zenetos et al., 2017).

The wide range of environmental tolerances, in conjunction with r-selected life cycle features (rapid growth, large fecundity and dispersing capacity), predisposes *C. sapidus* as a potential successful invader (Hill et al., 1989). In estuaries and lagoons, blue crabs can be crucial to the flow of energy and carry out a number of other ecological tasks. Blue crabs are both prey and consumers of plankton, tiny invertebrates, fish, and other crabs at different phases of their life cycle. They are significant scavengers and detritivores, and they may even be cannibals if food is scarce (Hill et al., 1989). They compete with other crabs for food and space, and they are hostile to other species (Gennaio et al., 2006; Nehring et al., 2008). Numerous parasites and illnesses, some of which have a great potential to cause mass mortality, are also hosted by *Callinectes sapidus* (Messick and Sindermann, 1992). Therefore, the ecology of the invaded settings may suffer greatly as a result of the arrival of blue crabs. Although *C. sapidus* has

established distinct permanent populations for decades, particularly in the eastern Mediterranean Sea where exceptionally high abundances of blue crabs have been observed, the precise long-term effects of this alien species on non-native environments remain unknown, despite the fact that it was named one of the 100 "Worst Invasive Alien species in the Mediterranean" (Streftaris and Zenetos, 2006).

Large populations of *C. sapidus* do, in fact, directly affect fishing operations by competing with other local species and causing damage to nets with their claws as well as to the fish that are captured (Kampouris et al., 2019; Marchessaux et al., 2023). For professional fisherman, especially in lagoons (Marchessaux et al., 2024), this damage results in higher expenses and decreased sales (Nehring, 2011; Perdikaris et al., 2016; Mancinelli et al., 2017b; Kampouris et al., 2019; Marchessaux et al., 2023).

Its abundance has increased rapidly in recent years, especially in recently colonized areas, to the point where it is now considered invasive. Both local productions, like the Manila clam in the Sacca di Goro and Sacca degli Scardovari lagoons in the northeastern Adriatic Sea, and native biodiversity, including competition with native species and the decline of several species toward extinction, have been significantly impacted by this (Prado et al., 2022).

2.3. Blue Crab Situation in Italy

Giordani Soika is frequently credited for recording *C. sapidus* in the Mediterranean Sea for the first time in 1951 (e.g., by Enzenroß et al., 1997; CIESM, 2008). Two specimens were reported by that author: an adult female collected in December 1949 off Caorle, north of Venice, and an adult male collected on October 10, 1950, from the lagoon of Venice, near Fusina. He identified them as *Neptunus pelagicus* A. Milne-Edwards, 1861 (syn. *Portunus pelagicus* (L.)), but Holthuis (1961) later identified them as *C. sapidus* based on Giordani Soika's description and illustration. Two *C. sapidus* specimens that Mizzan (1993) discovered in the zoological collections of the Natural History Museum of Venice and labeled as *N. pelagicus* were identified as the same as those that Giordani Soika had initially documented. The specimens'

dates and sampling locations, however, deviate from those reported by Giordani Soika (1951); the male crab was caught in the Venice lagoon on October 8, 1950, while the female crab was captured close to Marina di Grado on October 4, 1949. Although there are claims to its presence in the Aegean as early as 1935, it appears that Mizzan (1993) should be credited with the first confirmed record of the Mediterranean because that female was collected before the one mentioned by Giordani Soika. Mizzan (1999) came to the conclusion that *C. sapidus* had not formed a population in the lagoon since more individuals were found there in October 1991 and 1992 (Mizzan, 1993), but not in the years that followed (Nehring, 2011).

On the Adriatic coast of Apulia, blue crabs have been observed in two brackish lagoons: Varano lagoon during the summer of 2007 and Lesina lagoon from June to October of the same year (Florio et al., 2008). On the Salento peninsula, a specimen was also gathered close to Lecce, where fishermen caught it in January 2001. The steady population growth and its appeal to numerous stakeholders are confirmed by later records (Gennaio et al., 2006). According to Nehring (2011), *C. sapidus* appears to persist in these vast brackish basins in southern Italy.

A female *C. sapidus* was discovered close to the harbor of Messina in the spring of 1970, and another female was caught there in the fall of 1972 (Cavaliere & Berdar, 1975). Although specifics are lacking, *C. sapidus* was gathered during trawling surveys off the eastern coast of Sicily in 1988 and 1990 (Franceschini et al., 1993). The species' establishment in Sicilian seas is questioned by Pipitone and Arculeo (2003) (Nehring, 2011).

There are just three known examples from the Ligurian Sea: a huge male captured in a fish trap near La Spezia in the Gulf of Genoa in 1965, and two specimens from the port of Genoa and the surrounding seas obtained in 1962 (Tortonese, 1965).

2.4. Ecological and Economic Impacts of Blue Crab in Italy

Beginning in 2023, the Po Delta's clam and mussel farming operations—which for many years have been the primary and most lucrative economic pursuits in these regions—have been gravely threatened by the Blue Crab. According to Annex A of DGR No. 165 of February 20,

2024, the direct, quantifiable harm for Veneto alone is projected to be many tens of millions of euros during the first year of the crisis. An estimated 100 million euros will have been lost as a result of its invasion in 2024, and losses might increase to one billion euros over the following three years (Alberghini, 2024). Although it has not yet been included in the Implementing Regulation (EU) 2016/1141, which establishes a list of invasive exotic species of Union concern, the blue crab can already be regarded as an invasive alien species in the Po Delta's areas. It is sufficient to note that over 200 quintals of clams are harvested daily in Porto Tolle (Rovigo), and clam output has drastically decreased by 95% (Il Post, 2024). According to La Nuova Ferrara (2024), the circumstances in the Sacca di Goro are exactly the same. Despite the containment mechanisms put in place, the high concentration of Blue Crab in these areas makes it impossible to design new bivalve mollusc seedlings at this time, potentially compromising output even in the near future. Since the Blue Crab's population has now increased to a point where confinement is the only option, its extinction is unlikely. As a result, management techniques must be implemented. With nets that reach from the bottom to the top, farmers are now trying to construct enclosures to block off two or three hectares. On the one hand, the nets' mesh prevents the Blue Crab from swimming, but on the other, they must ensure the natural water flow and exchange conditions required for the mollusks' development and survival. In order to accomplish this, the nets must be cleaned at least once a day using specialized high-pressure cleaners that run on saltwater, but at least this method permits the cultivation of a small number of mollusks (Alberghini, 2024). Every day, hundreds of quintals of blue crabs are harvested, necessitating the use of alternative disposal methods. The most straightforward is encouraging people to eat blue crab. This is most likely the cause of the Blue Crab's exclusion from the list of invasive exotic species of Union concern, as all listed species are prohibited from being owned, transported, bred, released into the wild, and traded (EU Regulation No. 1143/2014 and Legislative Decree 230/2017). It is a food with a lot of nutritional potential because crab muscle is a great source of vitamins and minerals like calcium, iron, zinc, copper,

selenium, potassium, and phosphorus, as well as highly digestible proteins, essential amino acids, unsaturated fatty acids (particularly long-chain omega-3 fatty acids), and glycosaminoglycans (Nanda et al., 2021). The species *Callinectes sapidus* and the name "Granchio Blu" (GU General Series No. 21 of 26-01-2024) were added to the regulation of September 22, 2017 for "Italian language names of commercially important fish species" by MASAAF on October 18, 2023. However, the United States and Asian nations, where a developed market already exists, are currently the primary markets for the blue crabs that are fished in our regions. Exports are based on processed and frozen goods because fresh goods spoil quickly. In the initial months when the issue arose, there were no industries in the Po Delta regions that could process such a difficult product in amounts at least equal to the size of the crab population. Tons of semi-processed crustaceans harvested in the Sacca di Goro were initially sent to the US by the startup Mariscadoras Srl. Later, a number of further Veneto-based firms emerged to improve this product, which included both semi-processed and fresh ingredients (Il Gazzettino, 2023). The species, which is considered a valuable food source in its home region, is starting to gain recognition in Italy as well (Mancinelli et al., 2017; Kevrekidis et al., 2023). Although it is still occasionally found on Italian restaurant menus, it may be found at retail fish markets. Young businesspeople are also attempting to use the blue crab to add new flavors to their products. One such example is a young Venetian agricultural entrepreneur who has used blue crab to flavor her beers, drawing inspiration from the Irish custom of adding oysters to dark beers during the brewing process (Dire, 2024). Blue crab costs as much as 15 euros per kilogram in the early days of the problem's expansion and public attention, but the following overabundance affected prices, which now range from 1.5 to 9 euros per kilogram depending on the crab's size (La Repubblica, 2023). Since the part devoured, i.e., the muscle, is undoubtedly more numerous in adult males (jimmies), these specimens are primarily commercially valuable (Van Engel, 1958b). The price increases with the size. Freshly molted soft-shell crabs, which make up a small portion of the total catch, are also highly valued, most

likely because they remind buyers of the traditional *moeche* of *Carcinus aestuarii*, a species of crab that is currently in short supply due to the Blue Crab's detrimental effects on the ecosystem (Alberghini, 2024).



Figure 1. The IperTosano in Ferrara sells male blue crab specimens that were caught using pots and traps in the Sacca di Goro (FAO 37.2.1). 2.90 euros per kilogram. August 19, 2024 (Alberghini, 2024).

It is sold online as precooked, frozen, fresh, and processed meat in cans. A 200 g packet of tinned beef may cost as much as 35.90 euros (Alberghini, 2024).

3. Blue crab and Food Safety

From the perspective of food safety, given the applications and practices surrounding the consumption of shellfish, the issues with the blue crab are mainly chemical in nature rather than microbiological, such as the presence of heavy metals and compounds released from microplastics that the crab may consume from its surroundings (Alberghini, 2024).

3.1. Altering and Pathogenic Microorganisms

Fishery products can become contaminated by pathogens from the aquatic environment in which they dwell, from fishing nets and vessels to processing and transformation facilities, and from the humans who handle them. *E. coli*, *Salmonella spp.*, *Shigella spp.*, *Staphylococcus spp.*,

C. botulinum, and *Vibrio Parahaemolyticus* are often the potentially harmful bacteria linked to fresh fisheries products (ICMSF, 1980). The occurrence of *Vibrio parahaemolyticus* and, to a lesser extent, *Vibrio cholerae* and *Vibrio vulnificus* in blue crabs from Galveston Bay in Texas is described by Davis and colleagues (1982), particularly during the summer months. Protozoan parasites like *Toxoplasma gondii* and *Cyclospora cayetanensis* have been discovered in the Blue Crab, primarily in the gills and hemolymph, in addition to bacterial threats (Marangi et al., 2022). In comparison to meats and other foods originating from animals, fresh fisheries items are more likely to spoil both at room temperature and when refrigerated. The reason for this is that cold-blooded animals have endogenous enzymes and spoilage microbes that are active or viable even at low temperatures (Shaw and Shewan, 1968; Hobbs, 1983). Trimethylamine oxide (TMAO) is converted to trimethylamine (TMA) by a variety of spoilage bacteria, including *Aeromonas putrefaciens* and *Alteromonas*. This results in a potent and unwelcome fishy smell, indicating both a high bacterial population and quick product spoilage (Hobbs, 1983). Although most shellfish are eaten cooked, freezing slows down the rate at which food deteriorates but does not completely remove the possibility of contracting a foodborne illness when the goods are eaten raw. Accordingly, from a microbiological perspective, the problems are not so much the possibility of foodborne infections as they are the financial losses brought on by the product's degradation if it is sold fresh. It is frequently processed or sold live to get around this issue. Recontamination may have occurred as a result of contact with contaminated surfaces or utensils when the product is marketed already processed and ready to eat (Ready To Eat, or RTE) (Marshall, 1988). In cooked crab meat produced in the United States, Sivaranjani Pagadala and colleagues (2012) isolated both *Listeria spp.* and *Listeria monocytogenes*. This confirms that, like all other ready-to-eat foods, the product may be contaminated after processing, and the pathogen may multiply in the food matrix, especially if not stored properly. It's crucial to remember that both raw and pasteurized crab flesh have pH values between 7.02 and 7.79 and water activities between 0.975 and 0.985, which create an

ideal habitat for *Listeria monocytogenes* to proliferate (Parveen et al., 2017). As a result, careful consideration must be given to sanitary food handling, appropriate storage, and environmental disinfection (Alberghini, 2024). The European Union's food safety standards, as stated in Regulation EC No. 2073/2005, are *Salmonella spp.* in cooked shellfish and *Listeria monocytogenes* in RTE. (Alberghini, 2024).

3.2. Allergens

Undoubtedly, the fact that crab might cause an immune system reaction (the formation of IgE antibodies) in allergic people should not be disregarded, as it can occasionally result in anaphylactic shock (Alberghini, 2024). The edible portion of crab has been found to have 34 distinct thermostable low molecular weight allergens, making it one of the most common shellfish to trigger allergic reactions. Low molecular weight proteins are known to be allergens in shellfish, and the threshold level at which an immune system reaction can be elicited differs for each protein (allergen) and patient. The primary thermostable allergen responsible for allergic reactions, which frequently result in systemic reactions, is tropomyosin (Omgy and Vasunambisan, 2022). Annex II of EU Regulation No. 1169/2011 "on the provision of food information to consumers" lists 14 allergenic foods, including crabs. As such, the food business operator in charge of labeling the product must adhere to the regulation's labeling requirements in order to accurately inform the consumer if the product contains whole or part crab or if food containing crab is produced in the same facility. However, the consumer needs to read the label carefully, particularly if they have a shellfish allergy (Alberghini, 2024).

3.3. Heavy Metals

According to Çoğun et al. (2017), heavy metals are regarded as serious contaminants of the aquatic environment because of their toxicity, high persistence, lack of biodegradability, and propensity to bioaccumulate in plants. Anthropogenic or geochemical processes are implicated in their formation. According to the phenomena of biomagnification, heavy metals can

accumulate over time after entering aquatic species and subsequently humans through the food chain (Alibabić et al., 2007). Long-term exposure to heavy metals like lead and mercury is known to harm an organism's nervous system, interfere with reproduction, and cause cardiovascular disorders (Lee et al., 2014). Estuary blue crabs are prone to heavy metal accumulation because of their roles as scavengers, predators, and prey (Jop et al., 1997). Numerous investigations into the presence of heavy metals in specimens of blue crabs from around the globe concur that the amounts discovered are not insignificant. Nevertheless, a number of the metals discovered also have vital functions in crustacean physiology, which could account for some of the amounts; according to Farias and colleagues (2024), this could also explain why females had higher concentrations than males. However, because of their place in the food chain, Blue Crabs may be good bioindicators of contamination by heavy metals like cadmium that aren't thought to be necessary for the crustacean's life cycle (Kumar et al., 2000; Munuera et al., 2021; Farias et al., 2024). The tissues with the greatest accumulation are muscle, hepatopancreas, and gills (Çoğun et al., 2017; El Qoraychy et al., 2023). Furthermore, Çoğun and colleagues (2017) showed greater levels of heavy metals at the start of the summer period for Blue Crabs caught in Turkey, whereas El Qoraychy and colleagues (2023) discovered higher concentrations in the autumn for those caught in Morocco. These findings imply that seasonality may potentially affect the amounts of heavy metal buildup, however they are not totally consistent. This seasonality would need more research. In any event, it is crucial to remember that in order for shellfish to be marketed in the EU, assessments evaluating the product's adherence to the heavy metal restrictions established by EU Regulation No. 2023/915, must be carried out. Lead, mercury, and cadmium levels must therefore be less than or equal to 0.50 mg/kg (European Commission, 2023).

3.4. Microplastics

Plastic has become a ubiquitous element in daily life due to its massive expansion in use in recent decades (Hamad et al., 2013; Singh et al., 2017; UN, 2024). Due to the single-use nature

of the majority of plastic items, a massive amount of waste is produced. This is having serious negative effects on the environment, which are made worse by frequent poor trash management (Plastics Europe, 2021; UN, 2024). According to Lusher et al. (2017), improperly handled plastic garbage has the potential to evade waste management processes, find its way into the environment, and ultimately end up in the ocean. Plastic has consequently emerged as the primary waste material found in maritime habitats. Polyethylene (PE) and polypropylene (PP) packaging account for the majority of plastic waste, followed by polyethylene terephthalate (PET). Polyvinyl chloride (PVC), polystyrene (PS), and polyamides (PA) contribute less (Kaiser et al., 2017; Mio et al., 2021; Plastics Europe, 2021). Waste degrades and fragments in the environment due to the sporadic combination of solar radiation, cooling, heating, drying, and rain (Croxatto et al., 2021); as a result, different sizes of plastics—nano-, micro-, meso-, and macro—are created (Bettencourt et al., 2021; Table 1). Microplastics are described as a heterogeneous collection of materials in various shapes (fragments, fibers, spheroids, granules, pellets, shards, or beads) with sizes ranging from 1 μm to 5 mm in the 2016 EFSA (European Food Safety Authority) report (Table 1).

Field Descriptor	Common Size Divisions
Mega	> 1 m
Macro	25-1000 mm
Meso	5-25 mm
Micro	< 5 mm
Nano	< 1 μm

Table 1. Sorting plastic pieces according to their size.

According to Fortibuoni et al. (2021), the Adriatic Sea is thought to be the most contaminated part of the Mediterranean Sea. Given that the Po River is Italy's longest river and that millions of people live in Northern Italy, according to ISTAT data from 2024, the anthropogenic influence is substantial. Through the sewage system, vast amounts of waste of all types arrive at the Po and eventually end up in the ocean. For instance, the findings of Pellegrini et al. (2023) demonstrate that, in contrast to the majority of previous research in the literature, microplastics

are more prevalent in pro-delta environments and have a diverse distribution. In 2023, Cozzarini et al. also verified this. The dominating oceanic regime at the river mouth and the kind of river flood conveyance are the primary factors influencing the spatial heterogeneity of microplastic buildup (Pellegrini et al., 2023).

All commercially sold fishing items from all over the world that are meant for human consumption now contain microplastics (Alberghini et al., 2023). These investigations found that microplastics were mostly found in the digestive tract and infrequently found in edible tissues like muscles (Kwon et al., 2020). Furthermore, there are typically very little microplastics found.

Crabs are more likely than other marine creatures to consume microplastics because of their benthic habitats and predatory eating habits. Additionally, the water that passes through their gills might contaminate them. The digestive system collects microplastics from ingested food and sediments (Simantiris et al., 2024), but the gills' structure tends to trap and accumulate microplastics received from the water (Brennecke et al., 2015). These factors have led some to propose that the Blue Crab could serve as a sentinel organism for microplastic contamination in the environment or food chain (Renzi et al., 2020; Aliko et al., 2022). However, it is also true that certain sedentary and carnivorous crustaceans, such as *M. mercenaria*, tend to accumulate more microplastics due to their feeding habits than the opportunistic omnivore and swimmer *Callinectes sapidus* (Capparelli et al., 2022). According to a study conducted by Simantiris et al. (2024) on 77 specimens captured in Greece's Antinioti lagoon, blue crabs are impacted by microplastic pollution (MP) from an early age. 22 microplastics were found overall, with an average of 0.28 MP/individual, according to the findings of tests conducted on the gastrointestinal tract and gills. For instance, 39 adults from the Corpus Christi Bay in Texas had their stomachs found to contain higher amounts of microplastics (0.87 MP/individual and a prevalence of 35.9%) (Waddell et al., 2020). Six individuals caught in Puglia's Lesina lagoon had stomachs and female gonads with a higher average number of 2.5 MP/individual; no

microplastics were detected in the male gonads, muscle, or hepatopancreas (Renzi et al., 2020). However, when examining the variations in MP content among the gills, digestive tract, and muscles of blue crabs from the southeastern Gulf of Mexico lagoon, it was discovered that the gills and digestive tract had a higher prevalence than the muscle. Nevertheless, these variations were not statistically significant (Capparelli et al., 2022). Translocation of microplastics from the intestines or gills through the hemolymph is the most commonly accepted theory of how they could get to the muscle. On the basis of Bergey and Weis's (2007) research, Capparelli et al. (2022) speculate that microplastics might also stick to the muscle during the molting phase. However, Aliko et al. (2022) found that the gastrointestinal tracts of 30 specimens captured in the Kune-Vain lagoon in Albania had the most detrimental results of any study conducted to date on the presence of microplastics in blue crabs (43-50 MP/individual or 11 ± 1.85 MP/g). According to the same authors, Albania has the largest rate of unrecycled plastic waste, making it one of the most troublesome nations in terms of microplastic pollution. According to Capparelli et al. (2022), the majority of microplastics in the gills were fragments (41 fragments/g), but the majority in the digestive system were fibers (12 fibers/g). According to Torn (2020), the length of time that microplastics take to pass through crustaceans' digestive tracts varies depending on their size and type; it seems that while knotted fibers tend to accumulate more in the stomach, microplastic fragments that are consumed by crabs are easily expelled. The study by Waddell et al. (2020), which discovered a total of 24 fibers and 28 fragments in the stomachs of 39 Blue Crab specimens, is one example of literature data that contradicts this.

However, the review by Schmid et al. (2021) shows that there is no standardized method for analysis and that different analytical methods are frequently used, making it challenging to compare and analyze the data available in the literature on the presence of microplastics in seafood products in general.

Humans are most exposed to microplastics through the consumption of contaminated food and water. After being consumed, microplastics can enter the digestive system and be absorbed, leading to cytotoxicity, oxidative stress, and tissue translocation. Following exposure, microplastics may have a local effect in the intestine or travel via the bloodstream to other organs. When micro- and nanoplastics enter blood arteries, they can result in pulmonary hypertension, inflammation, vascular occlusions, cytotoxicity of blood cells by internalization, and a systemic inflammatory response (Canesi et al., 2015; Wright et al., 2017). Additionally, additives including polybrominated diphenyl ethers (PBDE), bisphenol A (BPA), nonylphenol (NP), and octylphenol (OP) that are either in their matrix or have already been absorbed from the environment can be released by microplastics (Alberghini et al., 2023). Persistent organic pollutants (POPs), such as organochlorine pesticides like DDT, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs), can also accumulate in ocean microplastics in addition to chemical additives. Once absorbed, these pollutants build up in fatty tissue (Rochman et al., 2015; Mato et al., 2001). Serious health concerns, such as endocrine disorders, cancer, cardiovascular illnesses, obesity, diabetes, and reproductive abnormalities, are associated with exposure to these pollutants. But as of right now, we don't have enough information to provide an accurate assessment of the hazards to human health (Alberghini et al., 2023). It is worth noting that, in any case, for the commercialization of crustaceans in the European Union, analyses must be conducted to evaluate the product's compliance with the environmental contaminants listed in Tables 2 and 3, as stipulated by Regulation (EU) No. 2023/915.

4	Halogenated Persistent Organic Pollutants				
4.1	Dioxins and PCBs	Maximum Content			Remarks
		Sum of dioxins (pg WHO-PCDD/F-TEQ/g)⁽¹⁵⁾	Sum of dioxins and dioxin-like PCBs (pg WHO-PCDD/F-PCB-TEQ/g)⁽¹⁵⁾	Sum of non-dioxin-like PCBs (ng/g)⁽¹⁵⁾	The sum of non-dioxin-like PCBs includes PCB 28, PCB 52, PCB 101, PCB 138, PCB 153 and PCB 180 (ICES - 6).

					Maximum levels refer to upper bound concentrations, calculated assuming that all values of various congeners below the limit of quantification are equal to the limit of quantification.
4.1.5	Fish products ⁽²⁾ and bivalve mollusks ⁽²⁾ , excluding products referred to in points 4.1.6, 4.1.7, 4.1.8, 4.1.9 and 4.1.10	3.5 pg/g fresh weight	6.5 pg/g fresh weight	75 ng/g fresh weight	For fish, the maximum level applies to muscle. If the fish is to be consumed whole, the level applies to the whole fish. For crustaceans, the level applies to muscle from appendages and abdomen; cephalothorax is excluded.

Table 2. The limits of dioxins and PCBs that are comparable and different from dioxins for crustaceans are discussed in an excerpt from EU Regulation No. 2023/915.

4.2	Perfluoralkyl Substances	Maximum content (µg/kg)					Remarks
		PFOS	PFOA	PFNA	PFHxS	Sum of PFOS, PFOA, PFNA and PFHxS	
							The maximum level applies to fresh weight. PFOS: perfluorooctane sulfonic acid PFOA: perfluorooctanoic acid PFNA: perfluorononanoic acid PFHxS: perfluorohexane sulfonic acid For PFOS, PFOA, PFNA, PFHxS and their sum, the level refers to the sum of linear and branched stereoisomers, regardless of chromatographic separation. Maximum levels refer to lower bound concentrations, calculated assuming all values below the limit of quantification are equal to zero.
4.2.2.2	Crustaceans and bivalve mollusks	3,0	0,70	1,0	1,5	5,0	For crustaceans, the content applies to the muscle of the appendages and abdomen; the cephalothorax is excluded. For crabs and similar crustaceans (Brachyura and Anomura), it applies to appendage muscle. For Pecten maximus, it applies only to the adductor muscle and gonad.

							For canned crustaceans, the limit applies to the entire content of the can. For the composite product, Article 3, paragraph 1(c), and paragraph 2 apply.
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Table 3. This is an excerpt from EU Regulation No. 2023/915 that governs the restrictions of perfluoroalkyl compounds for crustaceans.

4. Transformation of Blue Crab into a Food/Feed Resource

4.1. Revalorisation as Animal Origin By-Products in a One-Health

Perspective

Before the end of June 2023, professional fisherman in Veneto only brought commercially valuable specimens—adult males—to fish markets. Beginning in early July, all Blue Crab specimens—including those with no market value (females and juveniles)—were gathered and removed in order to dispose of them and incur the associated expenses, which now range from 0.25 to 0.50-euro cents per kilogram. The total quantity of blue crab handled in 2023 for the fish markets in the municipality of Porto Tolle alone was 992,586 kilograms (Annex A to DGR no. 165 on February 20, 2024; *Il Fatto Alimentare*, 2023). It is clear from these amounts that only a minor portion of the total volume supplied to the fish markets is affected by the exclusive commercialization of blue crab as food. Therefore, in order to lower disposal costs, other marketing tactics for the crab are required. Additionally, the substantial quantity of "waste" that is produced during the processing of blue crab in food businesses must be managed and disposed of. Therefore, entire crabs or their exoskeletons are the main things to be valued. New businesses are trying to create creative and sustainable prospects (Alberghini, 2024). Entire bodies or parts of animals, products of animal origin, or other products obtained from animals, not intended for human consumption are considered by-products in the European Union, as per Regulation (EC) No. 1069/2009, which establishes health regulations concerning animal by-products and derived products not meant for human consumption. Community regulation or an

operator's discretion may define by-products as such. Article 10 lists the following as category 3 by-products:

- e) animal by-products from the manufacturing of goods meant for human consumption;
- i) aquatic animals and their parts, with the exception of marine mammals, that did not exhibit any symptoms of diseases that could infect humans or other animals;
- j) aquatic animal by-products from facilities or plants that produce goods meant for human consumption;
- k) the following animal materials that did not exhibit any symptoms of diseases that could infect humans or other animals through them: i) the shells and carapaces of crustaceans and molluscs with soft tissues or flesh.

In accordance with Article 14, category 3 by-products may be used to make organic fertilizers or soil improvers, or they may be used to make feed for pets, fur animals, and farm animals if they have not undergone a decomposition process that would endanger public health. Taking this final point into account, crustacean meals made from the exoskeletons of crabs, shrimp, and lobsters are already manufactured all over the world as organic fertilizers. Plants can obtain slow-release nutrients from their exoskeletons, which are rich in chitin and calcium phosphate. Additionally, chitin stimulates a plant's immune system, which can help shield it from environmental stressors, illnesses, and pests (Crustacean Meal, 2024; Organic Gardening Solutions, 2024). One of the most prevalent aminopolysaccharide polymers on the market today is chitin, a polymer made up of many N-acetylglucosamine units joined by a β -1,4 bond (Alberghini, 2024). These polysaccharides are currently being chemically altered, biotechnologically engineered, or combined with other natural polymers to create functionally diverse active derivatives because of their affordability, high biocompatibility, and ease of availability (Yadav et al., 2019; Nanda

et al., 2021). According to Nanda et al. (2021), they have a wide range of uses in the fields of agriculture, the environment, food, textiles, medicines, and biomedicine (Figure 2).

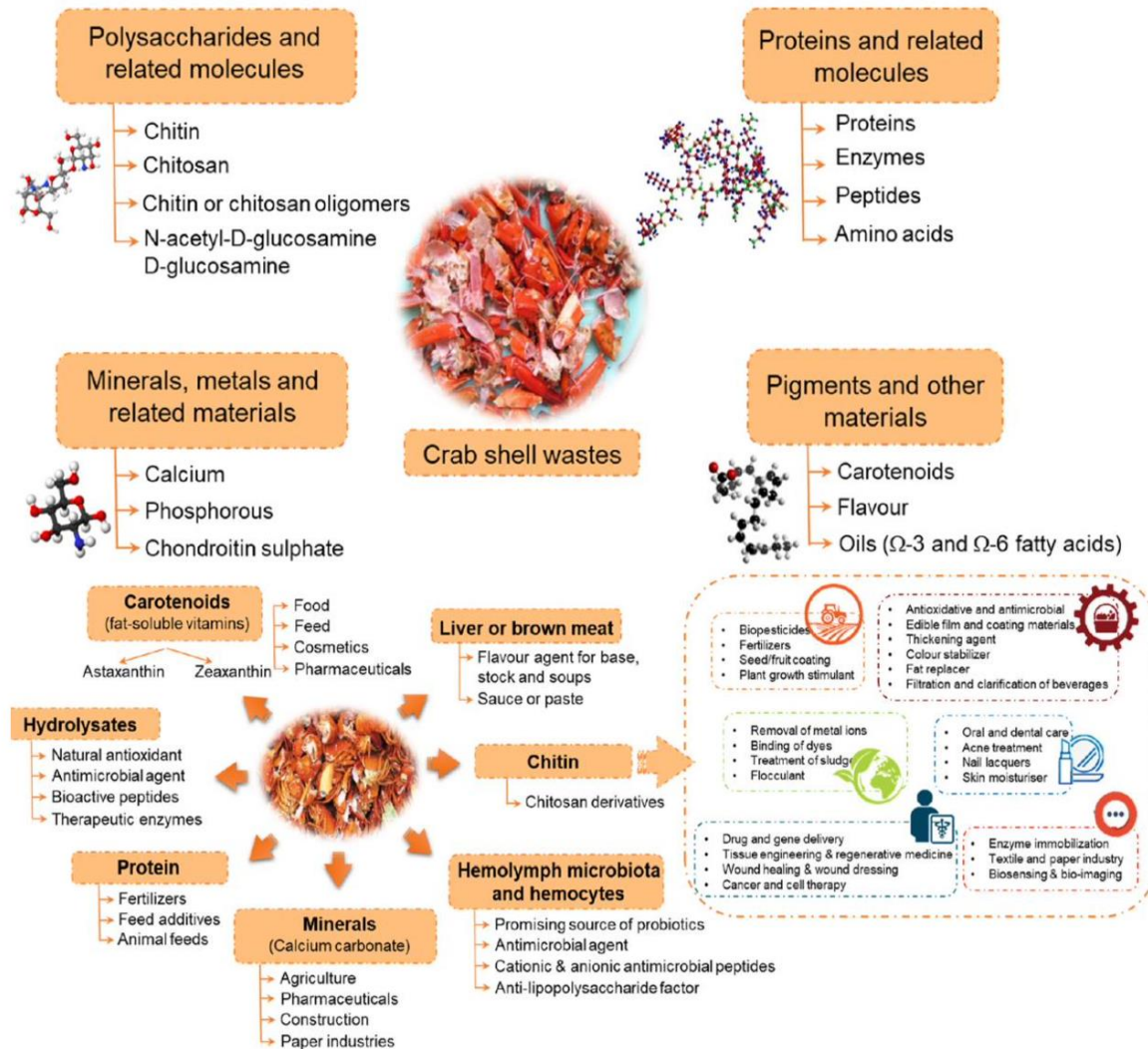


Figure 2. Crustacean exoskeletons provide functional and nutritional components that may find use in a variety of sectors (Nanda et al., 2021).

According to Wang et al. (2019), there are three conventional methods for extracting bioactive substances from fish processing by-products:

1. Techniques involving the application of chemical and/or physical agents to fisheries byproducts;
2. Enzymatic techniques that hydrolyze byproducts using enzymes (specifically, commercial proteases);

3. Microbial techniques that employ microbial fermentations and microorganisms to extract bioactive substances.

The usage of a number of cutting-edge techniques is growing, including ecological (green) extraction with natural solvents in conjunction with technologies like subcritical and supercritical extraction, microwave-assisted extraction, and ultrafiltration (Nanda et al., 2021). Excellent qualities of chitin include absorbency, non-toxicity, biodegradability, and biocompatibility. Traditionally, it is made from crab shells by chemically deproteinizing them with alkaline and then demineralizing them with acid. However, because of its superior solubility and compatibility, chitosan—one of the primary derivatives of chitin—has a vast array of uses (Alberghini, 2024). According to Wang et al. (2019), chitosan is a cationic polymer that can be produced by enzymatic hydrolysis in the presence of a chitin deacetylase or by N-deacetylation of chitin in an alkaline environment. Chitosan and its oligomers (such as chitooligosaccharides, chitobiose, N-acetylglucosamine, etc.) are non-toxic, hydrophilic, biocompatible, and biodegradable. They also have gelling, antimicrobial, antioxidant, anti-inflammatory, anticancer, and metal-chelating properties, according to Nanda and collaborators (2021), who cite a number of other studies. Because of these inherent and exceptional qualities, chitosan and its derivatives are highly sought after in the biotechnology, food, pharmaceutical, textile, cosmetic, and agricultural sectors. They may also find use in wastewater treatment, biomedical devices, and environmental protection. Chitosan's position as a useful component of food items and feed that benefits both human and animal health is well known, and the Food and Drug Administration has deemed it safe. Chitosan-based nano or microencapsulation is used to enhance the safety and quality of food items. It also works as a hypocholesterolemic agent and can decrease fat absorption when taken in small amounts as a dietary supplement. As prebiotics, chitosan and its oligosaccharides have anti-infection properties in addition to enhancing gastrointestinal function by promoting the growth of intestinal microbiota. Furthermore, the inclusion of crab meal in poultry rations was already being considered in the

United States in 1943. The meal was produced by heating the "waste" to 286°F in a steam drying tunnel (Lubitz et al., 1943). Several researches are still being conducted to determine whether blue crab may truly be employed in the field of animal feed, even after more than 80 years have passed (Alberghini, 2024). Together with the more well-known fishmeal, crustacean meal is listed in EU regulation no. 68/2013 regarding the catalog of feed products (Table 4). However, crustacean meals are not specifically included in the National Official Animal Feeding Control Plan (PNAA 2024–2026); instead, they are listed as "animal proteins other than those mentioned," and the only animal categories to which they might be assigned are adult ruminants (Table 5). According to Tabata et al. (2018), it should be noted that chitinase, an enzyme that catalyzes the hydrolysis of the β -1,4 glycosidic bond and facilitates the digestion of chitin found in food, including the exoskeleton of crustaceans, is only highly expressed in the stomach tissues of mice, poultry, and pigs. Although fish have a limited capacity to digest chitin, certain species, including the Atlantic cod (*Gadus morhua*), have been shown to exhibit chitinase activity when consuming crustaceans. This activity, however, may possibly be due to elevated chitinase levels in the food (Krogdahl et al., 2005). The utilization of crustacean meals, or at least those with a high chitin concentration, is undoubtedly limited by the varying levels of chitinase in different animal species (Alberghini, 2024).

Number	Name	Description	Mandatory Declarations
10.1.1	Aquatic invertebrates ⁽²²⁾	Marine or freshwater invertebrates, whole or in parts, in all stages of life, excluding species pathogenic to humans or animals.	Crude protein Crude fat Crude ash
10.2.1	By-products of aquatic animals ⁽²¹⁾	Products from establishments or facilities where products intended for human consumption are prepared or manufactured.	Crude protein Crude fat Crude ash
10.3.1	Crustacean meal ⁽²³⁾	Product obtained through heating, pressing, and drying of whole crustaceans or parts thereof, including farmed and wild shrimp.	Calcium Ash insoluble in HCl, if > 5%
10.4.1	Fish ⁽²²⁾	Whole fish or parts thereof: fresh, frozen, cooked, acid-treated or dried.	Crude protein Moisture content, if > 8%
10.4.2	Fish meal ⁽²²⁾	Product obtained through heating, pressing, and drying of whole fish or parts thereof, to which soluble fish compounds may be added before drying.	Crude protein Crude fat Crude ash, if > 20%

			Moisture content, if > 8%
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Table 4. Excerpt from Regulation (EU) No. 68/2013.

	Ruminant	Non-Ruminant Herbivores (horses, rabbits, etc.)	Pigs and Poultry	Farmed Fish	Pets and Fur Animals
Insect PAP	V	V	A	A	A
Fish meal	V**	A	A	A	A
Non-ruminant collagen and gelatin	A	A	A	A	A

Table 5. Excerpt from the PNAA 2024–2026

V: Prohibited

A: Authorized

* Intraspecies recycling is prohibited

** Fish meal is allowed for unweaned ruminants

Particularly for poultry feeding, a number of articles are starting to equate or at the very least recommend the simultaneous use of fish meal and crustacean meal. Some businesses in the Emilia-Romagna and Veneto regions also seem to have adopted this strategy, with the goal of using the waste from blue crabs to make chicken feed in particular (RM, 2023). Vijayalingam and associates (2020) conducted an experimental investigation to evaluate the nutritional content of two crab meals that were produced by drying the ingredients and then grinding them with a rotary grinder. They specifically contrast two meals that they refer to as “S”: meal from carapace and limbs and “V”: meal from pulp of the viscera and claws. The chitin content of the first is higher because it comes from the carapace and limbs, whereas the chitin content of the second is lower since it comes from viscera and fleshy claws. Table 6 presents the nutritional data.

S. No	Test	Crab Meal 'S'	Crab Meal 'V'
1.	Moisture	9.85%	18.00%
2.	Crude Protein	15.72%	33.55%
3.	Crude Fibre	11.66%	5.18%
4.	Ether Extract	0.57%	1.79%
5.	Total Ash	47.14%	35.08%
6.	Acid Insoluble Ash (Sand and Silica)	5.01%	11.61%
7.	Salt	2.21%	3.60%
8.	Gross Energy	2011 Kcal/kg	2528 Kcal/kg
9.	Calcium	19.45%	9.28%
10.	Phosphorus	1.18%	1.45%
11.	Iron	724.10 ppm	764.85 ppm
12.	Copper	69.07 ppm	96.58 ppm
13.	Manganese	162.37 ppm	153.36 ppm
14.	Magnesium	2.21%	2.45%
15.	Free fatty acids	5.21%	4.06%
16.	Myristic acid	1.02%	1.96%
17.	Palmitic acid	6.32%	17.86%
18.	Stearic acid	4.45%	6.78%
19.	Oleic acid	4.57%	16.62%
20.	Linoleic acid	3.15%	8.95%
21.	Linolenic acid	5.70%	0.72%
22.	Archieidic acid	0	2.48%
23.	Behenic acid	13.72%	8.47%
24.	Ecosapentaenoic acid	16.54%	9.43%
25.	Docosahexaenoic acid	15.28%	9.49%
26.	Palmitoleic acid	0.80%	2.52%
27.	Others	28.39%	14.67%

Table 6. Comparing the contents of "S" flour, which is made from the carapace and limbs, with "V" flour, which is made from the pulp of the viscera and claws (Vijayalingam et al., 2020).

Examining the findings:

- The calcium to phosphorus ratio (Ca:P) varied greatly throughout, ranging from 6:1 to 16:1. Due to a lack of endogenous phytase, chickens under normal dietary conditions have poor phytate phosphorus utilization. Therefore, it would be preferable to look at phosphorus that is not phytate. To maximize the absorption of these two minerals, poultry diets should have a 2:1 ratio of calcium to non-phytate phosphorus (Alberghini, 2024). The inclusion of crab meal without changing the calcium content of the diet may result in cataracts, nephrocalcinosis, appetite suppression, a general decline in growth rates, increased mortality, and decreased zinc bioavailability, indicating that attention must be paid to the contents of these minerals (Delgado et al., 2003). Nonetheless, some farming phases and practices—such as laying poultry—need higher levels of calcium and phosphorus (Alberghini, 2024; Poultry Hub Australia, 2024);

- Compared to the "V" meal, which contained just 11.61% total ash, the "S" meal had 47.14%. The total ash content of fish meal is typically 17–25%;
- Linoleic acid (18:2 ω 6) is the primary necessary fatty acid for poultry and is comparatively higher in "V" crab meal (8.95%). Nonetheless, approximately 1% is the very minimum needed for this group of animals (Alberghini, 2024; Poultry Hub Australia, 2024);
- The "S" meal has about 15% crude protein, while the "V" meal has twice that amount. According to Ravindran (2023) and Poultry Hub Australia (2024), the average demand for it in poultry is 19%. However, the specific amounts of necessary amino acids are not examined in this study. According to Richardson and associates (1985), crab meal has all of the essential amino acids needed for fish and poultry, but because it contains comparatively little lysine and tryptophan, the protein requirements of these animals may not be met. Therefore, tryptophan and lysine supplements may be necessary in order to completely substitute fish meal in designed diets (Alberghini, 2024).

With careful consideration, the results usually demonstrated the nutritional qualities of the crab meals taken into consideration in the study, supporting their potential use as a food supplement for poultry, particularly laying hens. In order to lower the cost of feed without significantly compromising its quality, the meal made from viscera and claws with pulp ("V") might also be added to feed used for the nutrition of farmed fish either in place of or in addition to fish meal (Alberghini, 2024).

There are currently no researches on the topic of microplastics in crustacean, and more especially blue crab, foods in the literature. Publications on the subject of fish meals do exist, nevertheless. Thiele and associates (2021) assessed two fish meals that are sold commercially. 52.0 ± 14.0 microfibers, mostly nylon, and 123.9 ± 16.5 microplastics, mostly polyethylene, were found in the samples per kilogram of fish meal. There may have been an increase during

the production process because the concentrations in processed fish meal appear to be higher than those in raw fish material. In Bangladesh, Siddique and associates (2023) discovered microplastics in all commercial fish meals they examined. There were 500–2200 MP/kg in the range. Instead, Jeyasanta and associates (2024) found microplastics in fish meals offered in India, with varying concentrations ranging from 210 ± 98.21 to 1154 ± 235.55 MP/kg. In conclusion, the vast amount of blue crab that reaches the Po Delta's fish markets today is sold as food, but it only makes up a small portion of all the crabs that are caught because there aren't any industrial facilities in the area that can process such a difficult product and are big enough to handle the issue. Time and money are needed for the conversion or building of new plants. As a result, the majority of the crabs are delivered to expensive disposal companies. One of the most promising alternatives to disposal would be turning the blue crab into meal for use as feed or as a raw material for feed. In order to determine its suitability for the different kinds of farm or companion animals, a number of researches are attempting to characterize it from a nutritional point of view. But generally speaking, feed and feed-related raw materials must abide by Regulation EC No. 1069/2009 and Regulation EU No. 142/2011. Additionally, Regulation EC No. 999/2001 may impose use limitations on feed (feedban). Additionally, Salmonella species must be absent, and PCB and Dioxin limitations must be adhered to, as mandated by PNAA 2024–2026. Microplastics are now prohibited from investigation by community legislation, and it doesn't seem like any studies on the detection of microplastics in crab meals have been published. Nonetheless, they are a growing issue on a global scale, and the media and scientific community are paying close attention to them (Alberghini, 2024).

5. Aim and Objectives

The present thesis project, developed in collaboration with the processing facility owned by the Consorzio Cooperative del Polesine O.P. Scarl, was primarily aimed at conducting a four-month experimental study focused on the transformation of whole blue crab (*Callinectes sapidus*) into an edible dehydrated product. The study placed particular emphasis on assessing food safety parameters, followed by a comprehensive evaluation of its nutritional quality. The ultimate objective was to explore and identify the most suitable strategies for its valorization within the market, thereby contributing to the sustainable management of this invasive species.

6. Material and Methods

6.1. Study Area: Scardovari Lagoon

Situated in the southern region of the Po River Delta, the Scardovari lagoon is a sizable embayment that spans around 32 km² (Fig. 3). Through a broad mouth that is partially blocked by a number of sand banks, this lagoon is connected to the Adriatic Sea. Over time, these banks' positions shift (Andreoli et al., 1994).

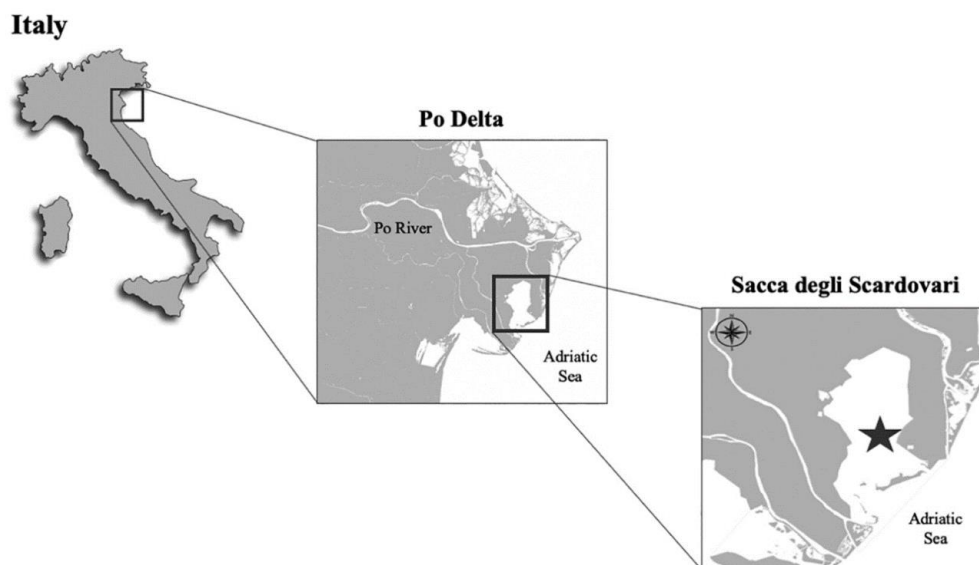


Figure 3. The geographical location of the experimental site (grey star) at Sacca degli Scardovari (Bordignon et al., 2020).

The Scardovari lagoon was formed in the first half of the eighteenth century, which is a very recent occurrence. This bay was formed by two delta branches of the Po River: Po di Gnocca in the south-west of the basin and Po in Tolle in the northeast. Except for two areas—one in the central channel dug by the inbound sea and the other in the east-central area, where the depth is 4-5 meters—the Scardovari lagoon's depth ranges from a minimum of 0.5 to a maximum of 2.8 meters (Andreoli et al., 1994).

Two distinct areas of this lagoon were identified thanks to hydrological, hydrodynamic, and sedimentological features reported by Cavallini & Paesanti (1979) and Colombo et al. (1979; 1981): an inner northern area that was less susceptible to marine vivification and a southern zone that was influenced by the tides and the fresh waters of the Po River. There are several pumps in the northern zone that create rainwater from agriculture, which is chemically rich, and then flows into the lagoon, boosting its nutritional content (Andreoli et al., 1994).

A broad outlet bordered with partially submerged sand banks connects the bay to the ocean. Due to the relatively narrow tidal ranges (annual maximum ranges of approximately 1 m at spring tide), the bottom is primarily made up of mud and is always submerged in water (Munari et al., 2013). While the southern end is impacted by exchange with seawater and is home to bivalve mollusk cultures (mostly clams and mussels), the northern section receives nutrient-rich, agricultural runoff. Seasonal blooms of opportunistic macroalgae in the most protected regions occur in late spring and summer due to eutrophication (Natali and Bianchini, 2018).

6.2. Consorzio Cooperative del Polesine O.P. Scarl

The Consorzio Cooperative del Polesine O.P. Scarl is a producer organization operating in the Po Delta, in the south of the Veneto region. Established in 1986, the consortium combines regional cooperatives that specialize in producing sand mussels (*Tapes philippinarum*) and mussels (*Mytilus galloprovincialis*), primarily in the Sacca degli Scardovari lagoon. The company is one of the most significant economic players in the area in terms of both product

quality and environmental sustainability, and the European Union has recognized it as a "Producer Organization (O.P.)".

Enhancing quality standards, guaranteeing traceability, adhering to shared marketing tactics, and coordinating the production activities of its members are the Consortium's primary goals. It also involves coming up with innovative ways to combat ecological dangers and environmental changes. In this context, the traditional mussel and sand mussel production in the Po Delta has begun to face threats due to the expansion of an invasive species, *Callinectes sapidus* (Blue Crab), in recent years. Different strategies have been developed by the Consorzio as a result of this new ecological scenario. In this regard, this thesis study was prepared in cooperation with the processing factory of Consorzio. In addition to examining product safety, nutritional value, and potential market usage areas, the study method attempted to dry invasive blue crabs and turn them into food. Thus, in keeping with the circular economy paradigm, the goal was not just to produce a food product but also to turn an environmental issue into a business opportunity. This collaboration demonstrates that the Consorzio Cooperative del Polesine actively participates in sustainability, innovation, and biodiversity conservation in addition to traditional manufacturing.

6.3. Description of the Experimental Setup and Dehydration Technology

The experimental activities will be carried out within the processing facility owned by the Consorzio Cooperative del Polesine O.P. Scarl, identified by EU approval number IT 47CDM. The installation of the equipment will be temporary (lasting four months) and will involve the use of the dehydration technology (W15), developed by the innovative start-up Feed from Food Srl, a Benefit Corporation (<https://www.feedfromfood.com/>). A chiller system will also be employed—this is a closed-loop liquid cooling system that, in line with sustainability principles, allows the W15 unit to recycle water during the dehydration cycles.

Specifically, the W15 unit installed at the Consorzio's facility will operate on fresh product one week per month (five working days) throughout the entire experimental period. The incoming quantity of fresh product processed by W15 will not exceed approximately 300 kg per day, with an average yield of dehydrated product estimated at around 36 kg/day.

W15 is a dehydration technology capable of processing and transforming various types of food matrices with different moisture contents through thermal treatment. The output is a dry product (with residual relative humidity $\leq 12\%$) suitable for edible use.

6.4. Description of the W15 Technology and the Dehydration Process

The W15 is a dryer that utilizes an innovative combination of mechanical fluidization and heated steam, resulting in a compact and highly energy-efficient drying system. The animal-origin product (AO), following a stunning pre-treatment achieved by immersing the live animal in a mixture of ice and water at a controlled temperature of $\leq -1^{\circ}\text{C}$ for 20 minutes, will be introduced into the feed hopper (Figure 4, A). The product will then undergo thermal treatment, during which the internal water content will be evaporated, leaving only the dry component—the “dehydrated product.”

The extracted moisture will be directed to a condensation chamber, where it will return to a liquid state and be externally discharged. During the trial period, the condensate will be collected in labelled containers or tanks and stored in the designated area of the laboratory annexed to the plant (Figure 4, C). The dehydrated product will be discharged through an outlet (Figure 4, B) and stored in bags suitable for the conservation of food and feed materials, properly labelled and identified (Figure 4, D).

The W15 unit does not emit vapours or gases into the atmosphere, which makes it suitable for installation in enclosed or indoor environments. The duration of the dehydration cycle is directly proportional to the technology's capacity (in this case, 15 kg of water evaporated per hour), the quantity and type of AO product being processed (in kilograms), and the average initial moisture content.

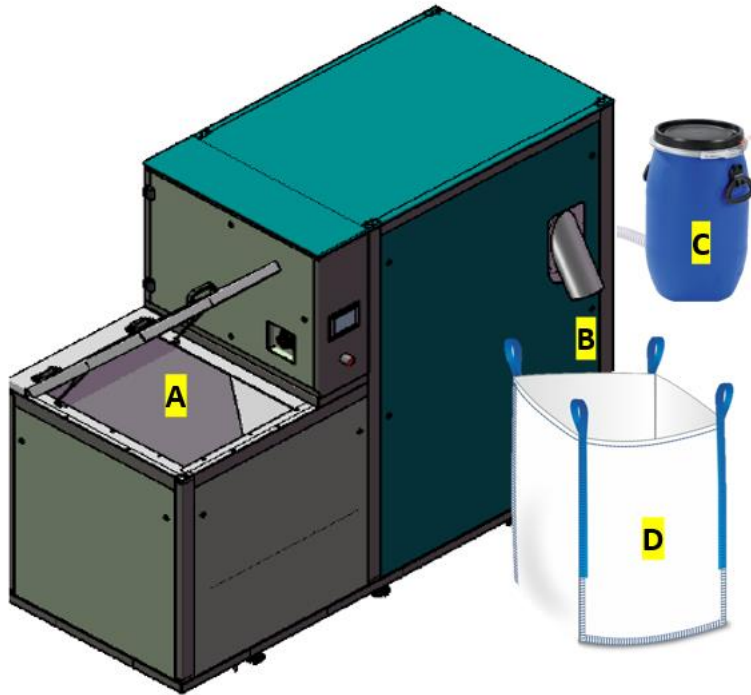


Figure 4. 3D View of the W15 technology

The Feed from Food process is protected under international patent PCT/IB2020/050872.

Specifically, the animal-origin (AO) product, following a stunning pre-treatment through immersion of the live animal in a mixture of ice and water (maintained at a temperature of $\leq -1^{\circ}\text{C}$ for a duration of 20 minutes), will be introduced into the loading hopper (capacity approximately 300–350 kg; Figure 5, A). From there, a screw conveyor located at the bottom of the hopper (Figure 5, B) will feed the material into the drying chamber (Figure 5, C).

Inside the drying chamber, the product will undergo thermal processing. Both time and temperature parameters are adjustable and can be modified at any moment, including via remote control. At the end of the cycle, the dehydrated product—featuring a customizable residual moisture content—will be automatically discharged into bags suitable for food or feed material storage.

The liquid by-products generated during the dehydration process will be collected in specifically labelled containers or tanks. These liquids will also be analyzed during the testing phase for research purposes.

Temporary storage of both the dehydrated material and the process liquids will take place in the laboratory area annexed to the processing facility. The entire process and supply chain will be fully traceable, both one step forward and one step back, through internal traceability systems. The food-grade dehydrated product will consist exclusively of whole blue crab, with no additional substances or ingredients.

Process initiation, shutdown, and parameter management are controlled via the control panel (Figure 5, D).

For a more accurate description of the process and in accordance with Regulation (EU) No 142/2011, consolidated version, Transformation Method 3 will be applied. In this method, the particle size of the category 3 animal by-products (ABPs) to be processed will be reduced to no more than 30 millimetres. The efficiency of the equipment will be checked daily, and its condition will be recorded in a dedicated logbook. If inspections reveal particles larger than 30 millimetres, the process will be halted and will only resume once corrective actions have been taken to address the non-compliance.

Following size reduction, the ABPs will be heated to ensure that the core temperature of the material reaches:

- over 100 °C for at least 95 minutes,
- over 110 °C for at least 55 minutes,
- over 120 °C for at least 13 minutes.

These core temperatures may be achieved consecutively or through a combination of the specified time-temperature parameters. The transformation process may be carried out using either a continuous or batch system.

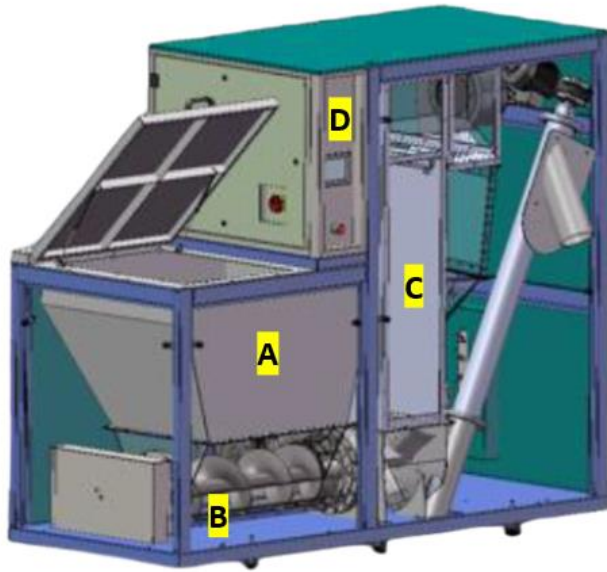


Figure 5. Frontal view of the W15 unit.

6.5. Edible Dehydrated Product: Food Safety Parameters and Nutritional Profile

All analyses were carried out at accredited private testing laboratories.

From a microbiological standpoint, compliance with the microbiological standards required by Regulation (EU) No 142/2011, consolidated version, was first verified:

Clostridium perfringens: absence in 1 g of product;

Salmonella spp.: absence in 25 g ($n = 5$, $c = 0$, $m = 0$, $M = 0$);

Enterobacteriaceae: $n = 5$, $c = 2$, $m = 10$, $M = 300$ in 1 g.

Where:

n = number of samples to be tested;

m = threshold value for the number of bacteria; the result is considered satisfactory if the number of

bacteria in all samples does not exceed m ;

M = maximum value for the number of bacteria; the result is considered unsatisfactory if the number of

bacteria in one or more samples is M or more; and

c = number of samples the bacterial count of which may be between m and M , the samples still being considered acceptable if the bacterial count of the other samples is m or less.

Subsequently, further analyses were carried out, specifically targeting staphylococcal enterotoxins (A, B, C, D, E), *Vibrio parahaemolyticus* and *Clostridia* producing botulinum toxins. Moreover, from a chemical perspective, heavy metals were considered, while from a physical perspective, microplastics were preliminary investigated. For the latter analysis, 5 aliquots of 10 g each were collected from batch one batch.

Finally, a full panel of proximate chemical analyses was performed in order to characterize the nutritional profile.

7. Results

7.1. Edible Dehydrated Product



Figure 6. The appearance of the edible dehydrated blue crab product after processing.

The W15 drying technology was used to convert the edible dehydrated blue crab product that was obtained for the study into a uniform, safe, and potentially profitable final product. The product acquired a physically strong form while preserving its structural integrity as a result of the dehydration process, making it suitable for both shelf life and transportation.

The final product has been uniformly dehydrated and has a stable structure in edible form. Its compact structure and smooth surface prevent it from breaking or cracking. The final product includes smooth edge lines and corners which are symmetrically and easily apparent, as seen in Figure 6. In addition to white, orange, and blackish hues that are thought to be linked to shell parts, the color tone additionally includes light brown, gray, and beige tones. This color distribution indicates that there is a balanced use of the grinding process and that the product contains both muscle tissue and shell material. The low gloss level indicates sufficient moisture removal and assured resistance to microbiological spoilage.

7.2. Food Safety Preliminary Results

7.2.1. Microbiological Results

The microbiological results confirmed compliance with the limits established by the applicable legislation.

Additional analysis results are presented in the Table 7.

Microbiological Parameter	Method / Reference Standard	Result
Staphylococcal enterotoxins (A, B, C, D, E)	UNI EN ISO 19020:2017	Absent in 25g/sample
<i>Vibrio parahaemolyticus</i>	UNI EN ISO 21872-1:2023	Not detected in 25g/sample
<i>Clostridia</i> producing botulinum toxins	ISS N-RL CNRB31.013 rev.3 (2023), excl. 13.5	Not detected in 25g/sample

Table 7. Microbiological safety analysis results of the fish meal sample derived from blue crab (*Callinectes sapidus*).

The crustacean meal samples from the blue crab (*Callinectes sapidus*) biomass assessed in this study was taken on May 6, 2025, and subjected to a number of microbiological analyses. On May 26, 2025, a preliminary results report was submitted. The analyses were conducted in compliance with the international standards (UNI EN ISO 19020:2017, ISO 21872-1:2023, etc.) that apply to food raw materials produced for human consumption. Three primary pathogen concerns are absent from the sample, according to the analysis's findings:

- Staphylococcal enterotoxins (A, B, C, D, E): the 25-gram sample did not contain any of these toxins. This indicates that the product has been processed under suitable hygienic conditions and food safety aspects and does not pose a risk to Public Health (EFSA BIOHAZ Panel, 2023).
- *Vibrio parahaemolyticus*: the presence of this bacteria, which is frequently encountered in seafood, has not been detected, and thus it is concluded that the product respect the food safety parameters and obtained from controlled sources (EFSA Panel on Biological Hazards BIOHAZ, 2024).

- *Clostridia* producing botulinum toxins: this microorganism with high toxicity was not detected in the analysis.

The methods used in each test comply with ISO 7218:2024 and ISO 19036:2019 standards and were calculated with a measurement uncertainty of 95% confidence level. The crustacean meal utilized as a sample is microbiologically acceptable and particularly appropriate for assessment in the animal feed industry, according to these results. Therefore, in terms of microbiology, the blue crab meal samples are at a level that does not prevent its use as a feed supplement or for consumption. These results support the product's marketability while taking into account the analysis dates and methodological reliability.

7.2.2. Microplastics Results

In one aliquot subjected to digestion (total of 5 aliquots of 10 g), the following were detected (Fig. 7):

One ruby-red, rectangular-shaped microplastic fragment (approx. 1 mm × 0.2 mm);

One blue-colored fiber fragment (approx. 5 mm in length).

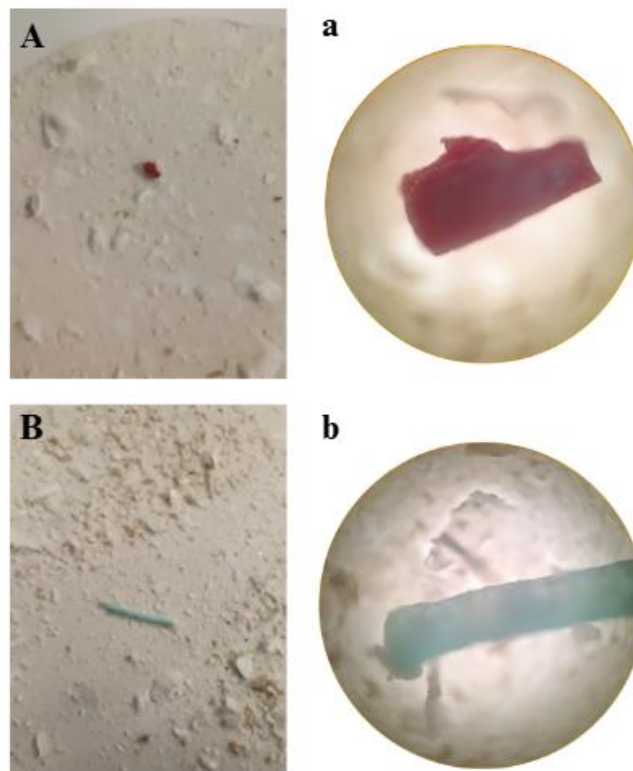


Figure 7. Visual Documentation of Microplastic Particles Detected After Digestion: (A, a) Ruby-red Fragment and (B, b) Blue-colored Fiber, (optical microscope; Jenamed 2, Aus Jena, 100x-1000x).

The prevalence of microplastics in food has been a major issue of concern for years, although there is currently no limit value. According to EFSA's 2016 scientific conclusion, microplastic particles in seafood at current levels do not represent a significant concern to human health. It was underlined, although, that more investigation is required before a definitive risk assessment can be made. In fact, the EFSA Panel concluded that even if a plate of mussels had hundreds of pieces of microplastic, the amount of chemical compounds they could carry would have no significant impact on total exposure (EFSA CONTAM Panel, 2016). The current finding shows that the amount of microplastics identified in the study's final product was low, indicating that the risk to human health is now insignificant, as expected by the EFSA.

7.2.3. Heavy Metals Results

Element	(mg/kg)
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Cadmium (Cd)	0.28
Lead (Pb)	2.41
Mercury (Hg)	0.079

Table 8. Heavy Metals Composition of Dehydrated Blue Crab (*Callinectes sapidus*) Product

According to the heavy metal analysis showed in Table 8, 0.28 mg/kg of cadmium, 0.079 mg/kg of mercury, and 2.41 mg/kg of lead were found. Lead and cadmium limits for shellfish were established at 0.5 mg/kg and 0.5 mg/kg, respectively, in accordance with EU regulation 2023/915 (European Commission, 2023). Cadmium levels in this area are adequate, but lead levels need to be closely watched. Although discussions on heavy metal levels are generally based on EFSA's risk assessment for human health, in our case these ingredients are included in pet food formulations. The inclusion rate is carefully calibrated, taking into account these reference values to ensure the final formulation remains within safe and acceptable limits for companion animals. xThe EFSA established a tolerable weekly intake (TWI) of 2.5 µg/kg body weight for cadmium due to its long biological half-life and potential to accumulate in the kidneys (EFSA CONTAM Panel, 2011). Even if cadmium levels are within established regulatory limits, long-term exposure should continue. According to Jarup (2003), prolonged exposure to heavy metals can have harmful consequences on the kidneys, cardiovascular system, and nervous system in human. In order for the final product to be used safely, the heavy metal content must be kept under control and monitored.

7.3. Nutritional Quality

Component	Value	Unit
Moisture	6.44	g/100g
Ash	41.10	g/100g
Protein (Nx6.25)	34.3	g/100g
Total Nitrogenous Substance	5.49	g/100g
Fat Content	3.93	g/100g
Saturated Fatty Acids	1.93	%
Monounsaturated Fatty Acids	<0.1	%
Polyunsaturated Fatty Acids	0.158	%
Carbohydrates (by difference)	14.28	g/100g
Sugars	<0.096	g/100g

Fructose	<0.096	g/100g
Glucose	<0.096	g/100g
Sucrose	<0.096	g/100g
Maltose	<0.096	g/100g
Lactose	<0.096	g/100g
Salt (sodium × 2.5)	2.52	g/100g
Sulfur	4450	mg/kg

Table 9. Nutritional Composition of Blue Crab-Based Product

A nutrient-rich profile appropriate for use as food or feed is revealed by analysis of the dried product made from the blue crab (*Callinectes sapidus*). As shown in the Table 9, the sample's low moisture content (6.44 g/100 g) is valued favorably in terms of microbiological safety and offers benefits for the product's shelf life.

The ash content was found to be quite high (41.10 g/100 g). This indicates that minerals such as calcium and magnesium are concentrated in the product, originating from the crab's exoskeleton and internal tissues. The product has a high protein structure, as evidenced by the observed protein level of 34.3 g/100 g. This makes the product suitable for alternative protein sources such as pet food or aquaculture feed.

Saturated fatty acids make up 1.93% of the 3.93 g/100 g total fat composition. Monounsaturated fatty acids persisted at a level too low to detect (<0.1%), whereas polyunsaturated fatty acids were found at 0.158%. The product's low fat profile indicates that it has a lean protein matrix, which could be useful in some diet formulations. By using a difference calculation, the amount of carbohydrates was determined as 14.28 g/100 g. Glucose, fructose, sucrose, maltose, and lactose were all detected <0.096 g/100 g below the detection limit. This indicates that there is hardly any sugar in the product.

Furthermore, the product contained 2.52 g/100g of salt (calculated as sodium x 2.5). In some nutritional applications, its content may need to be carefully controlled even if it adds to the product's flavor profile. Additionally, a comparatively high level of sulfur (4450 mg/kg) was found in the product. The presence of sulfur amino acids, which are crucial for protein quality and include cysteine and methionine, may be connected to this result.

These findings imply that blue crab can be dried and utilized as a low-sugar, high-protein product in the food and feed industries.

Nutrient/Element	Amount (mg/kg)
Vitamin B1	618
Vitamin B2	11.6
Vitamin B3 (Niacin)	221
Vitamin B3 (Nicotinamide)	108
Vitamin B5	1268
Vitamin B6	<9.1
Vitamin B9	24.2
Vitamin B12	31.8
Vitamin H (Biotin)	23.1
Vitamin A (Acetate)	<0.91
Vitamin A (Palmitate)	<0.91
Vitamin D3	<0.087
Vitamin E	28.7
Sodium	12970
Calcium	152200
Phosphorus	14622
Magnesium	7810
Potassium	7551
Copper	43.2
Zinc	85
Manganese	288
Iodine	7.99

Table 10. Micronutrient and Mineral Composition of Dehydrated Blue Crab (*Callinectes sapidus*) meal.

The high nutritional composition of the product and its potential as a food and feed ingredient have been confirmed by an analysis of the nutritional composition of the dehydrated final product made from blue crab, particularly with regard to vitamin and mineral content (Table 10). At 1268 mg/kg, vitamin B5 (pantothenic acid) had the greatest concentration of any B group vitamin. Niacin (221 mg/kg), vitamin B1 (618 mg/kg), and nicotinamide (108 mg/kg) were next in line. Through their role as coenzymes in energy metabolism, these vitamins promote cellular processes (Combs, 2012). The level of vitamin B12, which is essential for energy metabolism and the nervous system, was 31.8 mg/kg. Significant levels of biotin

(vitamin H, 23.1 mg/kg) and folic acid (vitamin B9, 24.2 mg/kg), which are critical for enzymatic and cellular growth, were also detected.

Vitamins A and D3, which are fat-soluble, have levels below the detection limit (<0.91 and <0.087 mg/kg). Processing techniques or seasonal biological variability could be responsible for this (Gropper & Smith, 2020). 28.7 mg/kg of vitamin E, which is well-known for its antioxidant properties, was found.

It is notable that the mineral profile has a high calcium concentration (152,200 mg/kg). The skeletal system's structural integrity depends on the minerals calcium, phosphorus (14,622 mg/kg), and magnesium (7,810 mg/kg) (Weaver & Heaney, 2006). High concentrations of macrominerals were also detected, including potassium (7,551 mg/kg), magnesium (7,810 mg/kg), and phosphorus (14,622 mg/kg). Minerals like potassium (7,551 mg/kg) are essential for nerve transmission and electrolyte homeostasis.

According to Prasad (2013), trace minerals including manganese (288 mg/kg), zinc (85 mg/kg), and copper (43.2 mg/kg) are important for enzymatic activity, immunity, and antioxidant defense. These results indicate that dried blue crab flour is a very nutritious matrix that may be assessed as a feed and food ingredient. This product is a sustainable source because it is high in calcium, B vitamins, and other vital elements. The information gathered is a positive step in turning the invasive blue crab species into an important resource.

8. Discussion

According to the results of the study, drying the invasive blue crab (*Callinectes sapidus*) can result in a product that is safe from a microbiological and physicochemical perspective. The microbiological analysis results of the dried product were found to be compatible with the food safety standards determined by the relevant laws. The evaluated samples did not contain enterotoxins from *Vibrio parahaemolyticus*, *Staphylococcus* species (A, B, C, D, and E), or *Clostridium* species that produce botulinum toxin. This indicates that potential pathogens were

effectively eliminated during the drying process and that the product was handled under suitable sanitary circumstances (EFSA BIOHAZ Panel, 2023; EFSA Panel on Biological Hazards [BIOHAZ], 2024). The findings of the study are in line with EU food safety standards, which state that cooked shellfish should not include *Salmonella* spp. and that *Listeria monocytogenes* should be below specific thresholds (Regulation (EC) No. 2073/2005; Alberghini, 2024). Furthermore, due to the low humidity rate (about 6.44%), the shelf life of the product is prolonged and microbial growth is inhibited by a decrease in water activity. In this regard, it is seen that using the right drying method can eradicate the fresh blue crab's risk of quick deterioration and microbial growth (Hobbs, 1983). However, as with any food product, care should be taken to reduce the potential of infection from cross-contamination or improper post-processing storage conditions. To reduce similar risks, sanitation and suitable storage conditions should be provided during the packaging and storage stages of the dehydrated product. For instance, it has been reported in the literature that *Listeria* may grow in cooked crab meat after processing (Sivaranjani Pagadala et al. 2012). The product produced from the blue crab may contain some elements derived from environmental contamination, according to the microplastic and heavy metal results evaluated within the limitations of chemical safety. Very minor levels of microplastic particles were found after the product was digested to make it digestible (a blue fiber of 5 mm in length and a red fragment of around 1 mm in size). According to a 2016 scientific opinion published by the European Food Safety Authority (EFSA), microplastic particles in seafood do not currently pose a significant risk to human health, despite the fact that their presence in food products has been a major concern in recent years (EFSA CONTAM Panel, 2016). As anticipated by EFSA, the fact that only trace amounts of microplastics were found in the final dried product in this analysis indicates a low level of health risk. The existence of microplastics, however, should not be disregarded entirely since it indicates the level of contamination in the environment that the invasive blue crab lives. Microplastics have been found to accumulate in the digestive tract, particularly in shellfish, and

to be less prevalent in edible components (Alberghini et al., 2023). This study concentrates on how the grinding of the entire product can allow these particles to enter the food. Thus, quality control should include monitoring microplastic contamination in blue crab-derived products, particularly in larger-scale production. Several toxic elements may accumulate inside of dried blue crab products, according to heavy metal tests. Specifically, the lead (Pb) level was 2.41 mg/kg. When compared to the highest amounts permitted in shellfish for human consumption, the value are excessive. For instance, the lead concentration of the final product is significantly higher than the 0.5 mg/kg upper limit for lead in shellfish set out in European Commission Regulation 2023/915 (European Commission, 2023). At 0.28 mg/kg and 0.079 mg/kg, respectively, cadmium (Cd) and mercury (Hg) levels are lower, below the allowable limits for shellfish (European Commission, 2023), therefore they represent a relatively low risk. However, it is important to proceed with caution when evaluating the presence of heavy metals in food or feed components. According to the literature, shellfish can bioaccumulate metals such as lead and cadmium from their environment, and it is well known that industrial and agricultural pollution leads to heavy metal accumulation in the lagoon and coastal ecosystems where blue crabs live (Kocatepe et al., 2013; Järup, 2003). This overall picture is also supported by the study's findings. The higher amounts of lead, in particular, indicate that this product could be better suited for evaluation as animal feed rather than for direct human consumption. The impact of heavy metal contents on animal health and indirect effects through the food chain should be considered, even when they are used in pet food or animal feed.

It is widely accepted that prolonged exposure to heavy metals can harm the cardiovascular, neurological, and kidney systems (Järup, 2003). Therefore, it is suggested to improve the environments where raw materials are collected, minimize pollution sources, and frequently monitor the product's heavy metal concentration in order to use dried blue crab product safely. Detoxification or heavy metal removal techniques that can be used during product processing (such as binding metals with specific chemical processes or using product components that have

lower metals) might be assessed in further research, if needed. As a result, it has become clear that although it is microbiologically safe, proactive measures should be taken regarding the chemical safety of the product, especially in terms of Pb and As. While the main focus of EFSA's heavy metal risk evaluations is human health, in our case, the primary focus is on the applicability of metals to pet food. In order to be sure the amounts used are within acceptable limits for domestic animal consumption, they were specially adjusted based on reference safety values. The dehydrated product derived from blue crab has a high nutritious content, according to the nutritional value data. The product has a high protein level of 34.3% (dry weight basis). The product can be evaluated as an alternative protein source due to its high protein content. Since the protein content is said to be higher (in the range of 50–70%) in shell-free products such as fish meal or pure crab meat, it should be noted that this value is lower than that of a typical fish meal since the product contains the entire crab (muscle tissue and shell parts) (Khamassi et al., 2022). However, according to a study on invasive blue crabs in the Mediterranean, its biomass has high protein and nutritional content, making it suitable for feed (Khamassi et al., 2022). The findings of this thesis show that significant amounts of protein may be supplied overall, even though the protein percentage is a little low for the product in shell form. The amount of this protein in pet food and farm animal feed formulas can be evaluated. The product has a comparatively low-fat level (3.93%), with saturated fatty acids accounting for the majority of the fat (1.93% of the total fat). Polyunsaturated fatty acids remained at 0.158%, while monounsaturated fatty acids were undetectable (<0.1%). Since it has low fat content, the product has a relatively low energy density and a lower risk of oxidative deterioration over its extended shelf life. However, the very low levels of essential fatty acids such as omega-3 indicate that the product may need to be supplemented in this regard if it is to be used as a sole feed ingredient. Omega-3 fatty acids, for instance, are often present in significant amounts in fish meal, however the dried product that is produced appears to be lacking in these nutrients, which may call for the use of additional fat sources in the formulation.

It can be concluded that the product has practically no digestible carbohydrates according to an analysis of the sugar and carbohydrate profiles. With <0.096 g/100 g (i.e., 0.096%) each, simple sugars such as glucose, fructose, sucrose, maltose, and lactose are below the detection limit. According to the difference method, the total amount of carbohydrates was 14.28%, which most likely consists of fiber-like components and indigestible polysaccharides like chitin. One component that fits within the category of dietary fiber is chitin, a structural polymer that is present in crab shells. Chitin digestion is limited in monogastric animals (such as pigs, poultry, and cats and dogs); yet, in certain species or with the aid of specialized enzymatic additions, it can be partially digested (Tabata et al., 2018). The presence of chitin in the dried product obtained as a result of the study reduces the energy value of this dried product, as it constitutes the majority of the carbohydrate fraction, but it also provides a potential source of fiber that supports intestinal health. Consequently, shell-derived carbohydrates, which constitute a significant proportion in the structure of dried blue crab flour, can be considered as a functional component (source of fiber) rather than contributing to its nutritional value.

The dried blue crab product has a relatively high ash (mineral) content (41.10%). This high ash level indicates that the product contains concentrated minerals from the crab's internal tissues and shell. Analyses in fact showed that the product had very high calcium (Ca) levels (152,200 mg/kg, or 15% of the product weight). Additionally, the levels of magnesium (7,810 mg/kg) and phosphorus (14,622 mg/kg) were notable. The presence of calcium and phosphorus at these levels suggests that the product may be a supplement that supports bone health in the diet of animals, as these minerals are essential, particularly for the skeletal system and bone formation (Weaver & Heaney, 2006). Due to its high calcium content, blue crab meal may be especially beneficial for the growth of young animals or for the diets of animals such as laying hens that have high calcium requirements. However, the formulation of feed must also carefully balance such high mineral contents. Alberghini (2024), for instance, emphasized that the overall dietary calcium level must be modified when incorporating blue crab crustacean feed products into the

diet; otherwise, excessive calcium could disrupt the mineral balance of animals. According to the literature, typical fish meal has a total ash content of 17–25% (Alberghini, 2024). The presence of shell material is mostly responsible for the study's 41% ash content, which is relatively high when compared to this reference point. According to reports, the ash concentration of one experimental crab meal that had only crab meat was as low as 11.6%, while another crab meal containing the whole carcass had an ash content as high as 47.1% (Alberghini, 2024; Poultry Hub Australia, 2024). Since the ash level of the dry product from the study is comparable to that of the whole carcass, it will be required to carefully regulate the calcium-phosphorus balance in the feed in practice. Adding crab flour in small amounts or combining it with other raw material sources (such as protein sources with less ash content) could be a way to address this. In certain circumstances, however, a high mineral concentration may be advantageous; for instance, it can reduce the requirement for additional mineral premixes in feed formulas that use crab flour. Analyzing the nutritional profile of the product indicates a notable abundance of vitamins, particularly those in the B group. Micronutrients known as B vitamins play a crucial role in energy metabolism and other biochemical processes as cofactors (Combs, 2012). With 1268 mg/kg, vitamin B5 (pantothenic acid) was the vitamin with the highest content in dried blue crab products. The following highest levels were 618 mg/kg of B1 (thiamine), 221 mg/kg of B3 (niacin), and 108 mg/kg of B3 (nicotinamide). At 31.8 mg/kg, the vitamin B12 (cobalamin) content is similarly quite high. These results show that B vitamins are abundant in crab biomass and that they are mostly preserved during drying. Vitamins B7 (biotin) and B9 (folic acid) were also found to be present in the product, with values of 23.1 mg/kg and 24.2 mg/kg, respectively. These vitamins are essential for enzymatic processes and cell proliferation. Vitamin A and vitamin D3, which are fat-soluble, are present at quantities below detectable limits (<0.91 mg/kg and <0.087 mg/kg, respectively). Vitamins A and D may be deficient in blue crab tissues or may be broken down during the drying process (Gropper & Smith, 2020). Alpha-tocopherol, or vitamin E, concentration was found to be 28.7

mg/kg. One advantage of the dehydrated blue crab product is that it contains a specific amount of vitamin E, which is well-known for its antioxidant qualities and for protecting cell membranes from oxidative damage. In addition to essential nutrients, the dried blue crab product contains significant micronutrients, according to a general analysis of the vitamin and mineral content. This shows that when the product is used as a feed or food supplement, it may provide a further nutritious contribution.

All of the information gathered is essential for indicating that blue crabs can be regarded as a feasible food source rather than as waste. The literature frequently emphasizes the concept of "converting the invasive blue crab species from a threat to a resource" (Mancinelli et al., 2017). This study provides empirical evidence that this change is achievable. The final product of the drying process is both nutritious (high protein and vitamin-mineral content) and safe (free of pathogens, stable, and traceable). Furthermore, the product's fluid powder/piece structure and physical resilience demonstrate its benefits in terms of processability and portability. This method has minimized the disadvantages specific to fresh seafood, such as its high moisture content and perishability. Nonetheless, there are a few things that must be taken into account when the product is being produced and marketed. Further studies may be needed in the future to address specific issues like evaluating the long-term effects on domestic animals, controlling factors like heavy metal accumulation that may limit food safety, and preserving product content consistency across batches and sources. In conclusion, the results examined in this discussion indicate that the dried product derived from blue crab has a generally favorable profile in terms of safety and nutritional content, while there is still time for development and some monitoring has to be done. In addition to providing as a foundation for further research, this study provides a significant contribution to the field of sustainable management and the introduction of an invasive species into the food chain.

9. Conclusion

This thesis study has shown that the *Callinectes sapidus* (Blue crab) species can be safely introduced into the food chain or feed industry by turning it into a dehydrated product. The information gathered indicates that the biomass of invasive blue crabs can be utilized as a beneficial input instead of as waste. Since the examinations did not reveal any pathogens or toxins that are significant for public health, the dried blue crab product created in the study is microbiologically safe. This demonstrates that the drying and processing techniques used are efficient and carried out in a hygienic manner. Upon physicochemical analysis, the safety criteria are mostly under control, despite the finished product having low levels of microplastic particles and lead levels that are above the limit. Hazardous elements such as mercury and cadmium are present in small amounts. Dehydrated product should be considered for long-term consumption since it has high lead concentration. The product's high protein content, high levels of B vitamins, and vital minerals (especially calcium, phosphorus, and magnesium) make it stand out in terms of nutritional profile. Low fat and moisture content improve stability and shelf life while reducing the chance of spoiling. Since the product is mostly made up of indigestible carbohydrates and contains almost no sugar, it has a low glycemic profile and fiber-like properties. Taking into account all of these characteristics, the dehydrated blue crab product is beneficial in terms of both its nutritional value and food safety standards.

The industry and literature on the evaluation of invasive blue crab as a possible feed and food ingredient have benefited significantly from this study. Drying blue crabs from the Po Plain (Italy) allowed for the first time a thorough safety and nutritional value analysis, which produced hard evidence supporting the invasive species' worth. The findings obtained show that, with the correct methods, this species (which causes issues for the environment and the economy) can be transformed into a valuable resource. In this regard, the study showed results supported the "transforming invasive into resource" approach that Mancinelli et al. (2017)

highlighted. In the pet food and farm animal feed industries, dehydrated crab products can be a substitute for conventional protein sources like fish meal. Therefore, it will be feasible to reduce the impact on the ecology and partially address the domestic feed raw material shortage by managing blue crabs and bringing them into the economy. Furthermore, it is recognized that the product presented in this study can be evaluated legally given that EU legislation permits the use of flour derived from shellfish as feed material (Regulation (EU) No. 68/2013). Another outcome of the study is that food processing waste can be reused safely and traceably using innovative drying technologies such as W15. This is a significant achievement in terms of food technology and sustainability.

Although the results of this study are encouraging, it is important to acknowledge its limitations and make recommendations for additional research. First, only a small number of samples and a single pilot production provide the basis for the analysis. Blue crab samples collected from various geographic locations or at different times of the year may have varying concentrations of heavy metals and microplastics. Thus, a more thorough understanding of the product's safety and consistency of nutritional profile will be possible in the future by repeating comparable analyses for other batches, geographical areas, and seasons. Second, the high concentrations of some contaminants in the dried product, such lead, might constitute practical limitations. Consequently, it will be important in the future to either discover methods to eliminate these metals during processing or to reduce pollution in the areas where blue crabs reside, such as controlling the sources of heavy metals in lagoons. For instance, techniques like removing specific crab tissues (organs where heavy metals build up) before processing or using chemical binders to lower the heavy metal level of dried product may be researched. Thirdly, live feeding should be used to assess the performance of the product. Although this study has shown that dried blue crab flour is safe chemically and microbiologically, it has not yet been examined how it affects digestibility, nutrient utilization efficiency, and growth/health when fed to various animal species (dogs, cats, chickens, fish, etc.). To determine the practical value and potential

drawbacks of this product, more animal feeding experiments are essential. Furthermore, research should be done on the long-term effects of blue crab flour's high ash and chitin content on the digestive system as well as how it interacts with beneficial microorganisms. Another important consideration is allergenicity: if the product is regarded as direct human food, people who are allergic to shellfish may be at danger. Tests and warnings against allergic hazards in human consumption (e.g. in the form of a dietary supplement) should thus be conducted. Although no significant allergic issues are anticipated for the target species when used in pet food, production workers and consumers should be aware of the potential for cross-allergy.

It is suggested that steps will be taken in the future to ensure quality and traceability. To establish a reliable supply chain, a traceability system that documents every step from the capture of the blue crab to the transportation of the product to the farm or final customer is required. The information gathered for this study also helps determine which critical control points should be prioritized by such a system (e.g., sorting the caught crabs based on size, avoiding processing batches that exceed specific contamination limits, etc.). Ultimately, as the product is being commercialized and scaled up, it is also critical to perform market acceptance surveys and economic analysis. The project's feasibility will be determined by the product's economical manufacturing, sustainable supply, and acceptance by possible consumers (pet food producers, feed factories, etc.).

The overall conclusion of this thesis study is that, through a regulated process, the invasive blue crab can be transformed into a valuable product. With respect to its high protein and mineral content, the dried product obtained from the blue crab may provide the feed sector an alternative raw material. The production of this product also contributes to restoring waste biomass to the economy and minimize the impact of invasive species on the ecology. Future studies may be able to address some of the limitations and development areas that have been highlighted. Consequently, this study provided a novel strategy from the viewpoints of sustainability and

food security; it has suggested a solution that complies to the One-Health principles to controlling an invasive species and provides benefits for the environment and the economy. It is expected that the results obtained in this scope will direct further research and serve as the basis for new initiatives related to blue crab evaluation.

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