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Review

History and Prospects for the Sustainability and Circularity of the Windowpane Oyster *Placuna placenta* Fishery in the Philippines

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Abstract: The windowpane oyster *Placuna placenta* lives in brackish coastal waters and has long been economically important to the Philippines because of its durable and translucent shell, which is used as a glass substitute and material for making windowpanes and handicrafts. There has been considerable degradation of the *P. placenta* fishery over the past decades. Moreover, there are waste and under-exploited by-products, such as the meat, which though nutritious and edible, currently has a very low value; its use is confined to dishes consumed by families in the fishing community. Historically, there have been instances of excellent practice in terms of regulating the *P. placenta* fishery, while in recent times, there have been local initiatives to restore this and to develop high-value food products from the meat. These initiatives have, however, never been followed through at a provincial or national level. Research on other molluscs and marine organisms highlights that these contain high-value pharmaceutical products, an unexplored facet of *P. placenta*. This review compiles evidence to establish the groundwork for an essential and comprehensive multidisciplinary research programme centred around the *P. placenta*, which would ensure a high value for all parts of the oyster, including those currently discarded. By fostering a sustainable and circular economy within this fishery sector and its associated industry, its economic value would be amplified. This is particularly important for oyster harvesters in the Philippines, who often find themselves on the economic ladder's lower rungs. By integrating the principles of a circular economy, this initiative would not only aim to uplift the economic prospects of these harvesters, but in doing so would drive the restoration of *P. placenta* to its former range.

Keywords: mollusc; bivalve; windowpane oyster; *Placuna placenta*; by-product; food; bio-active compounds; circular economy

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1. Introduction

Marine and freshwater organisms provide a range of essential foodstuffs and materials. Thus, the harvest of aquatic animals was estimated at 178 million tonnes in 2020, capture fisheries contributing 51% (USD 141 billion) and aquaculture 49% (USD 265 billion), with a total value of USD 406 billion [1]. While most is destined for human consumption, there are nevertheless 20 million tonnes destined for non-food use. Not surprisingly, given its geography, fisheries are an important part of the Philippines' economy. For example, in 2019, it ranked eighth among the top-producing countries and eleventh in the world for aquaculture fisheries production, with 2.07% and 1.01% shares in total fishery and aquaculture production, respectively, with the latter being valued at ~USD 2.05 billion in global aquaculture production [2]. The windowpane oyster (*Placuna placenta*) is one of the most important fishery products of the Philippines. It is a bivalve marine mollusc, which is known locally as "kapis", capiz, "pios", or "lamperong". Unusually for fisheries, it is the shell that has major economic value. This is well known to be a very versatile material for making aesthetic handicrafts, such as lamp shades, flower vases, and chandeliers, and can also be used for producing animal glue, chalk, shellack, soldering lead, and paint. The shell craft products are exported widely to economically richer countries [3]. *P. placenta* fisheries in the Philippines face important challenges, yet at the same time, local and small-scale endeavours demonstrate routes to overcoming these challenges. In this review, we use the natural history of the oyster and past and current practices in the fisheries to identify the challenges faced by the industry. We document the evidence for successful remedial action that could be implemented at a provincial and national level, the opportunities to harness economically valuable by-products, and identify new avenues for research that may yield further valuable by-products, and thus the introduction of a more circular economy for this oyster fishery. In addition, we identify some of the benefits of the oysters as proxy monitors for coastal water quality and physical stability.

2. Natural History of *Placuna placenta*

Marine bivalves are common in large numbers in coastal waters. Bivalve molluscs are thought to have originated in warm shallow euryhaline coastal waters and gradually invaded estuaries and brackish systems, as well as all the reaches of the world ocean [4]. In these systems, phytoplankton are consumed from tidal waters sweeping over dense beds of bivalves, mainly clams, cockles, mussels, oysters, and scallops. The dominant bivalves in these systems are adapted to changing temperatures and salinity, and some are adapted to exposure and wave action in the intertidal zone. Adult forms of the majority of these animals are benthic or bottom dwelling, and are therefore found burying within burrows in unconsolidated soft sediments; attaching byssal threads to pebbles or cemented to shells or rocks; and as semi-mobile members of the epibenthos [5].

Placuna placenta is the most common of the genus *Placuna* (established by Solander in 1786) belonging to the Family *Placunidae*, which is closely related to the Family *Anomiidae* [6]. It is the latter author who undertook and published the pioneering work on *Placuna placenta* [6]. Bivalves belonging to the Families *Anomiidae* and *Placunidae* have organs that exhibit a very high degree of asymmetry and distinctly inequivalve shells. The valves show a pronounced tendency to assume an orbicular outline and are very much flattened or laterally compressed, with the right bulb being almost flat and the left being weakly convex. In younger specimens, the shell is secured by a V-shaped ligament, is thin, and more or less translucent, becoming opaque with age and so has been considered to be 'mica-like' [7]. However, recent detailed physical analysis has demonstrated that the shell is 98.9 $\pm$ 0.1 calcite (calcium carbonate) and allows transmission of 80% of visible light [8]. Its thinness does not compromise its strength, by virtue of combining discrete biomolecular structures (composition and atomic structure unknown) within the calcite. In general, the oysters are harvested from 18 months, when the shell is $\geq$80 mm in diameter. Pigmentation of the adult shell is rare, though it is common among young forms to show a beautiful satiny pink or yellowish lustre. Despite common characteristics, *Anomiidae* and *Placunidae* have highly developed specializations: *Anomiidae* has calcified byssus, *Placunidae* has a single genital aperture, and the foot develops into a very long and trumpet-shaped organ [6]. The specific gravity of water in *P. placenta* oyster beds ranges from 1.019 g/mL to 1.015 g/mL at temperatures of ~30.5 °C to 32 °C. Unusually large influxes of fresh water during an exceptionally wet season entail the destruction of the oysters [6].

The valves of *Placuna placenta* seldom bear any parasitic growth of the type common in true pearl oysters [6]. It prefers brackish water and thrives best in areas with bluish-soft mud (fine silt, clays, organic material, and iron sulfide) or slightly sandy-muddy substratum in bays, coves, lagoons, and, in general, shallow areas up to 100 m deep, and can reach a diameter of up to 150 mm [9]. Unlike other bivalves, they cannot anchor themselves to the substrate, but rather rest on the sea floor. The bivalve is also a filter feeder, eating primarily plankton and organic waste [3].

The windowpane oyster *P. placenta* is highly prolific and periodically spawns [3]. The sexes are separate, as in the true pearl oysters, distinguished by the colour of their gonads with the genital glands opening into the kidneys [6]. Maturity of the bivalve starts at shell diameters of 70–100 mm, though gonads can be observed at sizes 50–80 mm. Reproduction is sexual, with fertilization externally taking place in open water, and a small number are hermaphrodites [3,10]. The oyster larvae gradually develop translucent shells and float with the current for approximately 14 days before settling on the bottom. As the oysters are predominantly immobile once they have settled on the sea floor, the species disperses and repopulates other areas by passive transport of the larvae through wave action and currents [10]. The distribution of *P. placenta* is from the shallows of the Gulf of Aden around India and the Malay Peninsula to the Southern coast of China and along the north coast of Borneo to the Philippines [9].

In general, bivalves exhibit changes in filtration rate, preferential filtration, and pre-ingestion sorting based on particle size, shape, surface chemistry, and filtrate composition. Rejected particles encapsulated in mucus are expelled as pseudofaeces before ingestion, while less nutritious items are rapidly egested as faeces. Concurrently, faeces and pseudofaeces repackage nutrients as biodeposits [5]. However, some of these aspects of oyster biology remain to be established for *P. placenta*.

3. Exploitation and Benefits Derived from Bivalves

Humans have long exploited bivalves as sources of food and products used in materials/building, concrete, fertilizer, and cultured pearls. Indirect benefits include shoreline stabilization and nutrient mitigation [5]. Other indirect benefits accrue from the fact they are filter feeders, and accumulate microorganisms and heavy metals [11,12]. These properties may mitigate pollution, but render the meat dangerous; however, they mean that bivalves such as the windowpane oyster *P. placenta* can be useful proxies for monitoring the quality of coastal waters. More recently, molluscs have been studied as a source of novel bio-active molecules.

3.1. Historical Perspective of Exploitation

Windowpane oyster is the name given by travellers in Southern China, which is derived from the use of the shell. *P. placenta* shells were extensively used in the Portuguese settlements in 1675 in India, because of the scarcity and cost of window glass. At the start of the 20th century, window glazing was seen in the Dutch Indies, in the Philippines, and in Canton and other districts of Southern China. The Chinese were the first to utilize the shell, and dissemination of this use is credited to the Portuguese [6], though without further historical evidence, this may reflect a European colonial perspective, since the extensive trading empires in Asia, e.g., the Austronesian [13] and later Indian maritime traders [14], may well have spread this practice.

P. placenta meat is edible, though the oyster has unusually extensive mucus, well above the small amount used to produce pseudo faeces in other molluscs. This mucus is simply removed by washing when preparing the meat (Section 4.1.2). While pearls of inferior quality are yielded in some quantity, it is the translucent shell that is today commercially and economically important. However, this was not always the case. *Placuna placenta* provided a fishing industry of local importance in four widely separated localities in eastern seas. Shells for glazing were half-grown (about 18 months old). These were then cleaned and polished by soaking, tossing, and shaking several times until dirt and roughness were removed and a translucent mica-like appearance was obtained [6]. Interestingly, there was a seed pearl fishery in North Bornean waters, which was less well-known, and therefore able to provide for sustainable exploitation by the Badjao divers (Malay inhabitants who, at the present time, are one of the cultural minorities in the Philippines currently known as sea gypsies, and scattered along the coastal areas of Mindanao) [15]. Historically, in this community, no shell was allowed to be fished under 10 cm in diameter and a license granted by the village chief (the duration of its validity is not recorded) was required before shells could be harvested. Badjao women and children shucked the shells, and pearls were obtained by slowly heating the meat over 3 days. After thorough cleaning, seed pearls obtained by the Badjaos were sold to Chinese dealers and exported to China where the bulk was used in preparation of folk medicines for the treatment of eye diseases and syphilis. Similarly, small pearls from Ceylon were also brought to India for use as components in native medicines or as a cosmetic, while bigger pearls were sold separately. *Placuna placenta* pearls have low value because of their small size, poor luster, irregular shape, and lack of hardness compared to gem pearls and the fanciful beliefs and traditions regarding medical uses of the pearls diminished with the progression of evidence-based medicine. However, the implementation of rules to govern *P. placenta* harvesting provides inspiration for the present day.

Philippine history traces the popularity of the shells to the 1860 edition of "Vocabolario de la lengua Tagala", the first dictionary of the Tagalog language [16]. Within it, the entry for capiz reads la Ventana (window). Pre-colonially, seashells were widely used in building, weapons, decorating clothing, and trading goods [17]. During Spanish colonization, churches and homes were built using capiz shells as a substitute for glass. Thus, *P. placenta* was the most common type of window material used in the Philippines between 1755 and 1960. The thin translucent shells were individually squared and then set like glass panes into wooden lattice frames to be used as window shutters, a unique feature of Philippine architecture from the Spanish colonial period (Figure 1). This includes the sliding windows of the 19th century. Such windows are also found in Goa in India. Today, the shells, are used in the manufacture of decorative items such as chandeliers, Christmas decorations, windowpanes, and many more [18], and from 1960, the shell served as the raw material of a lucrative export-oriented shell craft industry (Figure 2). Thus, *P. placenta* shell products are among the Philippines' most important fishery exports.

Figure 1. Example of a traditional Capiz window (photograph JMR, 20 June 2023, Samal, Bataan, Region III, Philippines).

Figure 2. Examples of commercial products made from Capiz shells (Photograph JMR, 10 July 2023; Kaliwanag Rural Improvement Club; San Juan, Samal, Bataan, Region III, Philippines).

3.2. Modern Economic Exploitation

P. placenta was once very abundant along the Philippine coastline. Before World War II, *P. placenta* processing was a lucrative industry in the province of Bataan. It is one of the indigenous seashells originally found in Samal and in the nearby municipalities of Abucay, Balanga, Pilar, Orion, and as far as Limay. However, the population of these bivalves has decreased. Contributing factors include the mechanized boats used by fishermen in collecting small pieces of stones or chips of sea shells locally known as "gasang", which destroys the natural habitat of the bivalve, and destructive methods of fishing and gathering such as trawling, using mechanical rakes and dredges, dynamite fishing, and compressor diving [10]. Thus, the high demand for this bivalve, both locally and internationally, has resulted in over-harvesting and habitat degradation [17]. In addition, the increase in prawn hatcheries may have also contributed to the decline in *P. placenta* harvests. In the late 1980s, prawn hatcheries flushed water laced with antibiotics back to the sea and the contamination may have killed *P. placenta* [19]. The result is a documented decline in harvest and revenue, recorded both locally and nationally.

Locally, in Bataan, based on the records of the Bataan provincial Agriculturist's Office in 2016, 248 tonnes of *P. placenta* were harvested and there was a reduction in the harvest of the shellfish to 154 tonnes in 2017 and to 138 tonnes in 2018; a 45% decline in just two years. The same scenario was repeated across all regions of the Philippines where *P. placenta* are harvested. Thus, the national export of shells and by-products for the country as a whole showed a substantial decline from 3260 tonnes in 1994 to 1765 tonnes in 1999, and just 731 tonnes in 2021 [2,20–22]. Consequently, the export of *P. placenta* products, which had an important economic impact on the Philippines, has suffered a major decline. From ranking fifth among the major fishery exports in 1991, and generating USD 33.5 million from 1989 to 1991 in shell crafts [23,23], it declined (USD 7.15 million in 1994 [22], USD 4.45 million in 1996 [21]) to USD 1.085 million in 2021 [2].

A combination of legal and remedial measures have been taken to try to reverse the decline of the *P. placenta* fishery. The Department of Agriculture Bureau of Fisheries and Aquatic Resources is responsible for implementing fishery regulations. Marine Protected Areas (MPAs; "no-take zones") have been established and these and other marine areas are protected by law from destructive activities. However, there is little that is directly applicable to *P. placenta* and much activity is devolved, for practice and implementation, by concerned institutions and fisheries agencies according to their programme mandates. There are monitoring systems and co-management by local communities/stakeholders, but there is no robust data acquisition to provide evidence relating to compliance or enforcement, which in part explains the continued decline of *P. placenta* harvests [24].

Some remedial measures have been taken, though these have been local, rather than across the entire historical range of *P. placenta*. Researchers of the Bureau of Fisheries and Aquatic Resources of the province of Bataan, Philippines, demonstrated that stock enhancement of *P. placenta* breeders can be made possible by enclosing a certain area using bamboo fencing with nylon nets, and by letting the oyster breed naturally. They recommended that the strict implementation of fishery laws, rules, and regulations could increase the production of the bivalve in the province [25]. In another study, it was found that the transplantation of *Placuna placenta* was feasible. Survival after three months of the oysters transplanted during the rainy season was 35–48% and 57–60% for those transplanted in the dry season, though larger ones only grew during the dry season. Gonad sizes also increased in weight over the three months, but more during the dry season. Among the larger individuals, gonads matured 3–4 months after transplantation and 60% of the animals spawned in June [26]. *Placuna placenta* with an average shell length of 10 cm were successfully spawned by raising the water temperature to 29 ± 0.5 °C. Three water treatment schemes were tested for larval rearing: chlorination, ultraviolet irradiation, and filtration (control). Larvae survived to the umbo veliger stage (180 µm, day 10) in chlorinated seawater, whereas mass mortality occurred at the straight-hinge stage in both UV-treated and filtered seawater. Eggs measured 45 µm on average, and fecundity was 5000–10,000 per female. Larvae were reared on a combination of the microalgae *Isochrysis galbana*, Tetraselmis sp., and *Chaetoceros calcitrans*, maintained at a density of 100,000 cells/mL [26]. It appeared that the combination of the diatom *I. galbana* and the green alga *T. tetrahele* enhanced gonad development in *P. placenta* more than using single algal species [27]. The Tigbauan coast, Iloilo, Philippines, had been depleted of the natural population of *P. placenta*, but retained the conditions necessary for their growth and development. Benthic organisms associated with plankton species needed by the animals for food were still abundant and, therefore, oysters could naturally repopulate the area. To achieve this, stocking was carried out during the first and last quarters of the year to avoid the rainy season, which could affect the restocking [10,28].

There are limited data on the efficacy of restocking, notably in the Panay Gulf beds. In 1999, it was confirmed *P. placenta* juveniles were observed within a year of restocking. However, gatherers collected the juveniles, including by means of illegal methods (trawls, dredges) despite calls to allow juveniles to mature and breed several more generations and the deployment of markers and buoys [29]. Thus, while there are fisheries regulations to control harvesting to protect the oysters and initiatives to restock, the high market demand for the shells and a lack of education, enforcement, and compliance results in gatherers continuing to collect shells with sizes less than 80 mm and more than 100 mm, and natural resources continue to be depleted [19].

3.3. Nutritional Benefits of Bivalves

Fish and seafood such as molluscs play a key role in human nutrition. Edible molluscs such as mussels, clams, scallops, and oysters are naturally low in carbohydrates, e.g., raw scallops, oysters, and mussels have been reported to contain between 3% and 5% carbohydrate [30], and lipids, but have a relatively higher content of unsaturated fatty acids. Moreover, they can be excellent sources of omega-3 fatty acids, vitamin B12, choline, and minerals such as iron, selenium, and zinc, and, in this context, have a similar or better nutrient value than some shellfish and land-based protein sources [30,31]. Marine bivalves are considered nutritious because they have high-quality protein, containing all the essential amino acids [32,33], as summarized by the proximate analysis of a number of bivalves (Table 1). The data in Tables 1–3 are reported in relation to wet weight, as there is no dry weight data for *P. placenta*. Whereas data on other species can include measurements of technical variation (multiple measurements on one sample), biological variation (multiple measurements on different biological samples), and seasonal variation, such information is not available for *P. placenta* and is omitted for the other species for the sake of clarity.

Table 1. Proximate composition of some common Philippine bivalves per 100 g wet edible weight.

Bivalve	Scientific Name	Moisture %	Ash %	Protein %	Fat %	Carbohydrate%	Ref.
Windowpane oyster	*Placuna placenta*	70.2	1.8	23.3	1.4	3.3	[34]
Philippine Slipper oyster	*Magallana bilineata*	82.64	1.01	9.41	3.25	3.2	[35]
Oyster	*Crassostrea* sp.	85.5	1.7	5.9	1.7	5.2	[34]
Mussel, green	*Perna viridis*	64.2	3.6	13.6	7.5	11.1	[34]
Clam, freshwater	*Corbicula manilensis*	78	0.7	7.6	1.9	11.8	[34]
Clam	*Cypraeidae* sp.	87.2	1.9	6.7	0.7	3.5	
Sea scallop	*Placopecten magellanicus*	78.50	1.6	17.4	0.48	1.99	[34,36]

Calcium is an essential component of the calcium carbonate shells of molluscan shellfish and it is recruited from seawater and deposited at fairly high concentrations in their tissues [30]. Thus, levels of calcium in shellfish are 2- to 10-fold higher than those found in beef, chicken, or pork. The United States Department of Agriculture National Nutrient Database shows that raw oysters and mussels are an excellent source of iron, with clams and scallops containing less iron. Thus, while scallops contain less than half the levels of iron of beef, chicken, and pork, oysters, mussels, and clams contain several times the amount of land-based meats [30] (Table 2). The high levels of minerals found in molluscs are also reflected in *Placuna placenta*. Because of the high iron content, a three-ounce serving of *P. placenta* provides 44% of the daily recommended intake. Although iron is important for red blood cell count, this mineral may cause hemochromatosis or the over-absorption of iron in the digestive tract [30]. However, a significant proportion of the population is moderately to highly iron deficient, and in the Philippines, zinc deficient too, the former being most common in women of reproductive age [37]. A number of essential vitamins are also present (Table 2). Of particular note is vitamin A, as deficiency in this vitamin can cause blindness, a problem that is prevalent in rice-based diets such as that found in the Philippines [38]. This highlights the potential of *P. placenta* to address this issue, at least in part.

Table 2. Vitamin and mineral content of some common Philippine bivalves per 100 g edible wet weight.

Bivalves	Vitamin A (retinol), µg	Thiamin mg	Riboflavin mg	Niacin mg	Na mg	Ca mg	P mg	Fe mg	Reference
Placuna placenta	95	0.02	0.11	1.4	467	110	257	17.3	[34]
Magallana bilineata	n.d. *	n.d.	n.d.	n.d.		159–175	518–530		[39]
Crassostrea sp.	110	0.21	0.2	1.7	882	147	77	5.9	[34]
Perna viridis	420	0.26	0.07	2.2	528	176	144	3.5	[34]
Corbicula manilensis	165	0	0.22	1.5	34	179	79	1.5	[34]
Cypraeidae sp.	130	0	0.16	1.5	645	153	125	7.3	[34]
Placopecten magellanicus	n.d.	n.d.	0.067	1.54	207	11	277	0.38	[40,41]

* n.d. no data.

Bivalve lipids have appreciable proportions of omega-3 long-chain polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Generally, the contents of PUFA are higher than those of saturated fatty acids and monounsaturated fatty acids (MUFAs) [41]. The contents of EPA and DHA in shellfish usually range between 300 and 500 mg% in raw muscle, and are generally lower than those of oily finfish such as Atlantic mackerel, salmon, and sardines [33,42] (Table 3).

Table 3. Fatty acids and cholesterol in some common Philippine bivalves per 100 g wet edible portion.

Bivalves	Saturated Fatty Acids, g	Monounsaturated Fatty Acds, g	Polyunsaturated Fatty Acids, g	Cholesterol mg	Reference
Placuna placenta	0.37	0.19	0.50	29	[34]
Magallana bilineata	0.48–0.61	0.13–0.22	0.27–0.36	31–35	[39]
Crassostrea sp.	0.44	0.23	0.61	35	[34]
Perna viridis	1.42	1.70	2.03	74.2	[34,39]
Corbicula manilensis	0.33	0.19	0.26	84	[34]
Cypraeidae sp.	0.14	0.09	0.14	22	[34]
Placopecten magellanicus	0.28	0.13–0.14	0.35–0.37	36.7	[34,43]

3.4. Pathogens, Allergens, and Contaminants in Bivalves

It is common to consume marine bivalves raw, steamed, or lightly processed [44]; consequently, they can act as vectors of a variety of pathogens (Table 4). This issue is compounded by the fact that bivalves are filter feeders and pathogen pollution is increasingly common in coastal waters. Moreover, bivalves contain allergens that can have major effects on susceptible people. Finally, the high content of certain nutrients can cause health issues.

Table 4. Pathogens in bivalves, divided into those with known human pathogenicity and those with no effect on human health.

Bacteria	Viruses	Parasites	Reference
	Pathogenic to humans		
Salmonella enteritidis	hepatitis A virus	*Echinocephalus sinensis*	[33,45]
Salmonella paratyphi	norovirus	*Sulcascaris sulcata*	[33,45]
Salmonella typhimurium	calicivirus	Giardia	[33,46]
Shigella spp.	astrovirus	Cryptosporidium	[33,46]
E. coli serotype O157:H7	-	Toxoplasma	[33,46]
Campylobacter spp.	-	-	[33]
Vibrio spp.	-	-	[33]
V. parahemolyticus	-	-	[47]
Aeromonas spp.	-	-	[33]
Plesiomonas spp.	-	-	[33]
Yersinia enterocolitica	-	-	[33]
Clostridium botulinum	-	-	[33]
Listeria monocytogenes	-	-	[33]

Table 4. *Cont.*

Bacteria	Viruses	Parasites	Reference
	Not pathogenic to humans		
-	-	pea crabs (*Pinnotheres* sp.)	[48]
-	-	*Tylocephalum* sp.	[48]
-	-	*Bucephalus* sp.	[48]
-	-	*Ancistroma* sp.	[48]

The presence of microbial pathogens and parasites because of the pollution of coastal waters can result in the contamination of bivalve shellfish by a variety of microorganisms [33,47], a problem compounded by the fact that bivalves are filter feeders and so can accumulate these pathogens in their tissues or organs [46]. The resistance of some of these pathogenic microorganisms to antibiotics and the tolerance of bivalves to heavy metals such as copper, lead, and cadmium can add further risk. The habit of consuming raw or lightly cooked bivalves increases pathogen-associated risks. Food-associated parasites are recognized as a threat to food safety and human health. Increasing globalization of the food supply, the trend of consuming food raw, and general ignorance about parasites add to this hazard [33].

The main helminth parasites of bivalves are trematodes, cestodes, and nematodes. Trematodes larvae are more important as bivalve pathogens than cestodes and nematodes. Infection in bivalves is most common in tropical and subtropical waters, where elasmobranchs constitute an important proportion of the vertebrate fauna [45]. *Giardia*, *Cryptosporidium*, and *Toxoplasma*, which are major parasites of humans and animals, may retain their infectivity in raw or undercooked molluscs. These are transmitted by contaminated water and food and can cause human gastroenteritis.

Some parasites are not pathogenic to humans, but may reduce the visual appeal of oysters, such as pea crabs. However, no serious parasites have been detected in stocks of commercially edible *P. placenta* in the Philippines. None of the parasites in Table 4 appear to be a problem due to either their low infestation level or low pathological effect [48].

In addition to the possibility of hemochromatosis alluded to above, oysters may cause stomach problems because of their zinc content; 85 g of oysters can contain 67 mg of zinc, which is enough to trigger gastrointestinal reactions, because it is more than the tolerable upper intake level of 40 mg per day. These reactions include vomiting, diarrhoea, and abdominal cramps. The problems caused by the zinc in oysters generally arise within 3 to 10 h of consumption and quickly fade after zinc levels return to normal [30].

Molluscan shellfish are also recognized as important food allergens. The prevalence of molluscan shellfish allergy is largely unknown, but may have parallel consumption patterns, with higher frequency in areas of frequent consumption [49]. The major allergen of molluscan shellfish is their tropomyosin, a muscle protein, which elicits IgE binding in the sera of half or more of patients with shellfish allergies. It was first identified as the major allergen from shrimp and later recognized as a pan-allergen among invertebrate species including crustaceans and molluscan shellfish; e.g., squid, octopus, cuttlefish, mussels, scallops, and oysters. Although bivalves are likely to be the most frequently ingested class of molluscan shellfish, the existence of allergic reactions to bivalves is rather poorly documented in the medical literature. The prevalence of allergies to oysters, clams, mussels, scallops, and cockles has been reported in different countries, but these were mainly based on surveys without any diagnostic follow-up. However, evidence for the existence of mussel allergy is reasonably strong because of sensitivity to mussels by the presence of mussel-specific IgE in patient's blood serum [50]. Arginine kinase (AK) has more recently been identified as a novel allergen in *Crassostrea angulata*. After cloning to produce recombinant AK (rAK), it was found that native AK and rAK had similar IgG/IgE-binding activities and physicochemical properties, and exhibited cross-reactivity among oysters, shrimps, and crabs after the serological analysis of oyster-sensitive individuals [51].

The accumulation of metals and human pathogens by bivalves also provides an opportunity because bivalves tolerate these contaminants. Their immobility and wide distribution allow bivalves to be used for monitoring the concentration of such pollutants in coastal areas [12]. They also remove contaminants by being hyperaccumulators of Cu (*Crassostrea virginica* [2013 mg Cu kg^{-1}]), Pb (*Mytilus edulis* [506 mg Pb kg^{-1}]), Cd (*Pinctada albina* [108 mg Cd kg^{-1}]), and Al (*Crassostrea rhizophorae* [2240 mg Al kg^{-1}]), and have approached this status for Zn (*Crassostrea virginica* [9077 mg Zn kg^{-1}]) [11]. However, there is no information yet regarding the hyperaccumulation of heavy metals by *P. placenta*. Similarly, with respect to human pathogens, allergens, and contaminants, there are no systematic data on the *P. placenta*. The above considerations of other molluscs indicate that this is an area ripe for investigation.

4. Potentials/Processing Possibilities for *P. placenta* By-Products

Marine animals such as bivalves are a rich source of bio-active compounds (briefly summarised in Section 4.1), though the potential of *P. placenta* in this respect is unknown. There have been local initiatives to develop products based on *P. placenta* meat, but as described in Section 4.2, these have not been followed up. Moreover, while there have been a considerable number of studies that have assessed the nutritional value of oysters and other molluscs, only one analysis has been performed on *Placuna placenta*, reported in the Food and Nutrition Research Institute's published Philippine Food Composition Table (PhilFCT), which has nutrition facts of different Filipino foods (Tables 1–3). How robust these data are and how variable they may be in terms of location and season is not known. Thus, although consumers and researchers interested in *P. placenta* meat can consult the Philippine Food Composition Table for reference, the information listed in the Tables is limited to proximate composition, some minerals, vitamin content, and fatty acid composition. A more thorough investigation of the biochemical characteristics of this bivalve needs to be conducted to determine the processing potential and safety of its by-product meat for human consumption.

4.1. Bioactive Compounds in Marine Invertebrates

4.1.1. Peptides

Marine organisms significantly contribute to economic and research development because these are a major part of the human diet, and many contain bioactive compounds. Their complex habitats and exposure to extreme conditions, such as salinity, pressure, temperature, and illumination result in marine bio-active peptides differing in terms of their sequences and properties from those derived from land animals. It has been suggested that because marine organisms are in close contact with microbes they are, consequently, a substantial source of antimicrobial peptides [52]. Thus, in recent years, researchers have isolated antimicrobial peptides from a variety of marine organisms, including oysters, and these peptides are safe, natural, inexpensive, and exhibit high bio-activity.

4.1.2. Shell Proteins and Polysaccharides

The shells of molluscs can be considered to be a specialised extracellular matrix; $CaCO_3$ crystals are embedded in a matrix of protein and polysaccharides, which control the shell mineral deposition, and many of the proteins have been characterised [53,54]. However, since the *P. placenta* shell in itself is of high value, the use of its proteins and polysaccharides would only be feasible for the waste from the shell processing industry and would require the identification of a high-value protein or polysaccharides, such as ones with therapeutic activity. Anecdotal data indicate that *P. placenta* contain a large amount of mucus, commonly referred to as 'slime', to the extent that the traditional processing of the meat starts with extensive washing to remove this. Thus, there may be high-value compounds in the shell waste, the meat, and the mucus. Although to date nothing is known about the proteins and polysaccharides in *P. placenta*, examination of what has been found in other marine organisms supports the contention that this is an area ripe for investigation.

4.1.3. Glycosaminoglycans in Marine Invertebrates

Glycosaminoglycans in molluscs and other marine organisms have received considerable attention as a potential alternative source of heparin, a World Health Organisation essential drug, following the 2008 heparin contamination scandal, where batches of anticoagulant heparin were contaminated with over sulphated chondroitin sulphate, resulting in the deaths of patients [55]. Glycosaminoglycans are characteristic of all multicellular organisms [56], and genes likely to encode their biosynthetic enzymes [57] have been identified in choanoflagellates, which are considered to be the descendants of the last common unicellular ancestor of multicellular organisms. Importantly, the glycosaminoglycan chondroitin sulphate has been isolated from a choanoflagellate and demonstrated to regulate sexual reproduction, one of the functions of GAGs found in multicellular organisms [58]. It is, therefore, not surprising that molluscs contain glycosaminoglycans.

The GAGs in marine organisms may be even more structurally diverse than those in land vertebrates (reviewed [59]). A unique HS from bivalve *Nodipecten nodosus* has disaccharide units chain composed of nonsulfated, 2-O-sulfated, or 3-O-sulfated GlcA, as well as 2-N-sulfated and/or 6-O-sulfated GlcN, and the anticoagulant activity of the mollusc HS was 5-fold lower than that of porcine heparin [59] The GAGs of the marine clam *Anadara inaequivalvis* are enriched in dermatan sulfate; 58% of total GAG content, with CS and HS contributing 16% and 26%, respectively [59]. The bivalve *Mytilus galloprovincialis* produces considerable amounts of hyaluronic acid of an average size of 200 kDa; HA from other sources is used as a filler for wrinkles in the cosmetic industry [59]. The freshwater bivalve, *Anodonta cygnea*, has been shown to contain heparin, that is structurally analogous to that of bovine lung heparin, with an anticoagulant activity similar to that of porcine intestinal heparin [60].

The considerable work carried out on shrimp GAGs provides further support for research on marine sources of GAGs. The shrimp *Penaeus vannamei* has emerged as a promising reservoir of bioactive glycans. One such compound, resembling heparin in its structure and function, has demonstrated remarkable anti-inflammatory effects [61]. This shrimp heparin-like compound not only reduced inflammatory cell migration to injury sites in acute inflammation models, but also exhibited the ability to mitigate matrix metalloproteinase (MMP) activity, which is crucial for tissue remodelling. Impressively, its anti-inflammatory potential surpassed that of mammalian heparin while displaying minimal anticoagulant activity. Similarly, a novel heparin/heparan sulphate-like compound from the shrimp's head has been identified. Although distinct from conventional heparin or heparan sulphate, this compound displayed shared structural features, including *N*- and 6-*O*-sulfation, as well as comparable glucuronic acid content [62]. Notably, this unique compound exhibited significant anticoagulant activity in aPTT and Factor-Xa inhibition assays, consistent with its ability to stabilise antithrombin III [63]. This shrimp compound's dual attributes of potent anticoagulation and minimal haemorrhagic effects set it apart as a potential alternative to mammalian heparin.

The exploration of marine-derived glycans extends beyond their anti-inflammatory and anticoagulant activities to encompass their role in angiogenic processes. Heparin and heparan sulphate's ability to modulate angiogenic factors and cytokines has prompted an investigation into the potential of a shrimp-derived heparin-like compound in this realm. An unusual heparin-like molecule containing significantly high amounts of glucosamine 3-O-sulfation [64] was found to interact with growth factors crucial to angiogenesis, such as fibroblast growth factor-2, epidermal growth factor family members, and vascular endothelial growth factor, leading to the inhibition of endothelial cell proliferation. Furthermore, its impact extended to modulating the architecture of capillary-like structures and reducing the choroidal neovascularisation (CNV) area [65].

The multifaceted properties of marine-derived glycans, particularly the shrimp heparin-like compounds, showcase their potential as valuable candidates for addressing diseases, including neovascular age-related macular degeneration and other antiproliferative disorders, offering a fresh avenue for therapeutic development based on natural sources. The above work in shrimp-derived heparin/heparan sulphate, alongside that carried out on some bivalves and extensive studies on tunicate-derived glycosaminoglycans (reviewed [66,67]), highlights that there is ample justification for exploring the activities of GAGs from bivalves such as the *P. placenta*, both as sources of existing drugs, such as anticoagulant heparin, and novel ones. Moreover, since most of these compounds are derived from by-products generated during their commercial exploitation (such as shrimp heads), this would exemplify a successful implementation of the circular economy paradigm. This endeavour not only aids the food industry, but also holds the promise of deriving potential pharmaceutical resources from waste materials. This, in turn, could have far-reaching effects on waste management practices and enhance the environmental sustainability of these products, contributing to their "green premium".

4.2. *P. placenta* Oyster By-Products and Waste

Fish and other aquatic organisms are processed into various food and non-food products. During the processing of *P. placenta*, large amounts of by-products are underutilized, if not wasted. The harvesting of *P. placenta* provides local fishermen not only income from selling translucent and durable shells for the shell craft industry, but also cheap and nutritious protein sources for their families [3] (Figure 3), though as noted above, over-reliance on this food source may cause issues. A more efficient utilization of the by-products of *P. placenta* processing would reduce the problem of disposal and subsequent environmental pollution. Furthermore, the shellfish will be valorised, which would elevate the nutritional and economic status of the fishing community, wherein *P. placenta* processing is one of the primary industries.

Figure 3. Shucked *P. placenta*, showing the shells prior to processing and the meat. (Photograph JMR, 20 June 2023, Samal, Bataan, Region III, Philippines).

Notable amongst the local initiatives to develop *P. placenta* meat is the work of the Chairman of the Kaliwanag Livelihood Association (KLA) of Samal, Bataan, who enthused that they hope to make *P. placenta* a major source of income for town residents, and if every member of the organization got involved, the benefits would increase and the oysters' shells and meat would become distinctive products of their town. Thus, the Mayor was of the opinion that the molluscs should be one of the prime commodities of the town, claiming they harvest about 250 tonnes per year, which are then made into various products [68].

Thus, members of the Kaliwanag Rural Improvement Club of Samal, Bataan, engaged in the development of *P. placenta*-based products, utilized the oyster meat in processing chips and fermented oysters [25], and standardized recipes of dishes with the oyster meat as the main ingredient [69]. It has been claimed that although "kapis" chips are smaller than mussel chips, the product is tastier and very rich in protein [69]. However, these claims are not yet supported by any systematic and controlled analysis regarding nutritional value (which can alter during processing), sensory evaluation, shelf life, and so on. In part due to the lack of such scientific underpinning, the efforts of advocates of *P. placenta* meat processing and their efforts in the transfer of knowledge to develop the industry have not been sustained, and the oyster has not entered the Philippine national food system. Consequently, although *P. placenta* meat is edible and has potential as a raw material for producing low-cost nutritious products, it still has very low value and its use is confined to local dishes and consumed by families in the fishing community, and so does not provide extra income to the gatherers and shuckers. Thus, rigorous development of *P. placenta* meat products and their analysis will be important to promote its wider consumption, contributing to more balanced nutrition. Importantly, the technology of processing the meat should not be limited to making chips and cracklings. Since *P. placenta* meat is already used as the primary ingredient in locally cooked dishes, studies of such dishes should be conducted to make these dishes more acceptable, stable, and guarantee their safety to the consumer. The latter would include rigorous quality control to exclude dead oysters and any harvested during the bloom of toxic algae (colloquially known as 'red tides'). Consequently, these products have yet to enter the higher value urban food system and these ambitions have not been firmly established locally, let alone nationally, or been supported by systematic analysis of the quality and safety of the products to support the marketing of products.

Which glycosaminoglycans are present in *P. placenta* meat and their properties is unknown. Another source of polysaccharides and likely other bioactive compounds is the extensive mucus slime, which is currently discarded. However, nothing is known about its molecular composition or biological activities. Given the number of potentially useful bioactivities discovered in other molluscs, which range from anticoagulant heparins to antimicrobial peptides, it is likely that analysis of the mucus would provide products and active structures that could be synthesised in clinically useful quantities.

5. Conclusions

Exploitation of the windowpane oyster *Placuna placenta* has considerable potential economic and social benefits. Achieving these will require research programmes ranging from developing food products that can enter the food system, generating additional income for the oyster harvesting communities, to the analysis of the mucus slime to identify bioactive compounds. In parallel, given the extensive destruction of the oyster beds through over-harvesting, often by inappropriate means, an effort to regenerate the oyster beds and effectively regulate harvesting is required. While the means to do so are established, their implementation at scale may require the incentive of increasing the economic value of the *P. placenta* through the exploitation of the meat and other by-products. The need for quality control of food and medicinal products would, in turn, provide a proxy monitoring of the quality of coastal waters. In addition, restoration of the oyster beds would contribute to the physical stabilisation of the coasts, which is increasingly important in the face of global warming and the increased number and strength of typhoons experienced by the Philippines. A multidisciplinary research programme to harness developments in these different areas and promote the appropriate development of the *P. placenta* industry into new avenues would thus be timely.

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