A Global Overview of Aquaculture Food Production with a Focus on the Activity's Development in Transitional Systems-The Case Study of a South European Country (Portugal)

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Review

A Global Overview of Aquaculture Food Production with a Focus on the Activity's Development in Transitional Systems—The Case Study of a South European Country (Portugal)

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Abstract: World aquaculture food production rises every year, amounting, by 2018, to another all-time record of 82.1 million tonnes of farmed seafood, with Asia leading global production. In Europe, although coastal countries present historical fishing habits, aquaculture is in true expansion. Norway, the leading European producer, is the eighth main producer worldwide. Portugal is a traditional fishing country but has invested in the development of aquaculture for the past decade, attaining, by 2018, 13.3 tonnes produced, making Portugal the 16th main producer amongst European Union member states that year. Most Portuguese aquaculture facilities operate in coastal systems, resorting to extensive and semi-intensive rearing techniques. In Portugal, marine food production in transitional systems is particularly interesting as the practice has, worldwide, been continuously substituted by intensive methods. In fact, facilities in transitional systems have developed over time and products gained higher commercial value. Clams and oysters corresponded, together, to over three quarters of total mollusc production in Portugal in 2018, while gilthead seabream and European seabass made up nearly all fish production in coastal environments. The state of aquaculture practices worldwide is reviewed in the present work, providing a particular focus on Portugal, where considerable development of the aquaculture sector is expected.

Keywords: aquaculture; rearing methods; transitional systems; Portugal case study; world aquaculture production

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1. Introduction

Although dating back thousands of years, aquaculture has only recently experienced great development worldwide.

It is unclear when aquaculture practices began, but findings over the years suggest the activity has existed for centuries. The first steps in this production may date back to the Neolithic age, around 4000 B.C., focusing on trapping aquatic animals in small waterbodies for them to be available at any time needed [1]. Pictorial engravings on ancient Egyptian tombs, dating from 2500 B.C., represent the harvest of tilapia from artificial ponds; the rearing of carps in China, dating back to the fifth century B.C., is probably the most well-known evidence of ancient aquaculture activities. In Europe, Romans fattened fish in tanks that were primarily aimed for the rearing of oysters or for salt production, but it was only during the Middle Ages that European communities took the first steps in aquatic animals' rearing, growing fish, especially carps, in monasteries' ponds [1–3].

Aquatic animals' farming in transitional environments also began to develop around that time in Southern European countries, where coastal lagoons and ponds were used to maintain fish brought in by the ocean tide, usually alternating with salt production in the same areas. As for the farming of molluscs, its early development dates to the 13th century, and organisms, especially oysters and mussels, were produced in pole cultures, spreading along the French Atlantic coastline during the 19th century; Northern European countries, on the other hand, developed bottom cultures for the rearing of the same organisms [1,3].

Aquaculture worldwide experienced significant development from the beginning of the 20th century, and, around the 1970s, awareness of the negative impacts that years of intensive fishing had caused on wild fish stocks raised an ecological concern. This contributed to greater development of aquaculture activity and discussion about its benefits and importance from either ecological or economical perspectives. Hence, around that time, aquaculture practices began to be regarded not only as a means to obtain seafood complementary to capture fisheries, but also as a way of releasing the overpressure on wild stocks and producing organisms to restock overexploited wild stocks.

The development of fisheries and aquaculture enabled populations to search for more diversified diets, which, together with the awareness of the health benefits associated with seafood consumption, led to an increase in the demand for such products. According to the Food and Agriculture Organization (FAO), seafood production from capture fisheries has stabilized since the 1980s, whereas aquaculture production has increased, almost hand-in-hand with the growth in seafood consumption worldwide [3].

The present review aims to gather a concise overview of the status of aquaculture practices worldwide, stress asymmetries regarding production across the globe—between and within continents—and raise questions about the development of the activity and its impact at different scales. Moreover, the work focuses on the case study of coastal aquaculture in Portugal, which has resorted to extensive and semi-intensive rearing. These methods are, nowadays, almost obsolete in most Southern European countries—which have transitioned to mostly intensive methods of production—but thrive in Portugal.

2. Methodology

To characterize the status of aquaculture worldwide, published work regarding the sector was searched for each continent and deepened for major producing countries, as well as for Portugal, as case study. Two main sources were used for data analysis: (i) the Food and Agriculture Organization (FAO) regular publications on the state of fisheries and aquaculture [4] and FAO statistics [5]. Although the most recent publications on capture fisheries and specific information regarding aquaculture in particular countries date to 2019 or 2020, the most comprehensive data collection regarding the aquaculture sector worldwide dates to 2018 [4,5], which is the reason for considering the year 2018 as reporting year in the present review; (ii) the Portuguese National Institute of Statistics (*Estatísticas da Pesca*) (INE) [6–9], which constitutes a "grey" area for data accessibility as the published information exists only in Portuguese, being less accessible for a wider public.

For simplification purposes, the term "seafood" will be used in this work to relate to all aquatic animals aimed for human consumption, including finfish species, molluscs and crustaceans.

3. A Global Overview

The volume of aquaculture products' supply for human consumption surpassed the supply for the same purpose from capture fisheries for the first time in 2014 [4,5]. In 2018, the total world aquaculture seafood production accounted for about 82.1 million tonnes, valuing an estimate of 250.1 billion US dollars, with fish being the main cultured group, valuing about 139.7 billion US dollars [4,5]. Marine and coastal aquaculture of aquatic animals corresponded to 37.5% of total world aquaculture, of which 56.2% was of molluscs' production [4,5]. Although freshwater and diadromous fish supply surpassed that of capture fisheries for the first time in 1986 and 1997, respectively, and despite marine fish farming being in true expansion, it is considered unlikely to surpass supply from capture fisheries in the near future. This may be due to various reasons, including the fact that not all desired species can be currently produced in aquaculture (either due to technological constraints or unprofitability compared to capture fisheries), and the public's perception of the quality—usually in organoleptic terms—of aquaculture products. This last possible explanation is most common in fishing countries, which, especially nowadays, may be biased by traditional behaviour and habits alone, coupled with a lack of information about the quality of farmed seafood. All this influences the acceptance of aquaculture products, maintaining the demand for captured products [4,5,10,11].

Global aquaculture production of aquatic animals has been growing at an average rate of 5.3% in the period 2001–2018, although a decrease to 4.5% was recorded between 2016 and 2018. This is attributed to a lower production in China, the world leading producer, which resulted in a decreased world growth rate of 4% in 2017 and 3.2% in 2018. Although the rest of the world combined also witnessed a slower growth rate in production, it still presented a rate of 6.7% and 5.5% growth in 2017 and 2018, respectively [4,5].

Asia is the leading continent in marine, coastal and freshwater seafood aquaculture production, both in terms of volume and estimated first-sale value, producing in 2018 about 88.7% of the total volume of aquaculture products worldwide. The Americas are the second continent with the highest production in terms of volume, accounting for 4.6% of the total aquaculture production, followed by Europe, which contributed about 3.8% of world production. Africa produced about 2.7% of the world's farmed aquatic animals in 2018 and Oceania accounted for the production of less than 0.25% of total world aquaculture products in volume in 2018 [4,5]. Although Asia is the leader in aquaculture production concerning both volume and value, as mentioned above, the products farmed in The Americas and Europe especially, sustain greater market value per volume unit [4]. The contribution of the different types of aquaculture environment for each continent total production is represented in Figure 1.

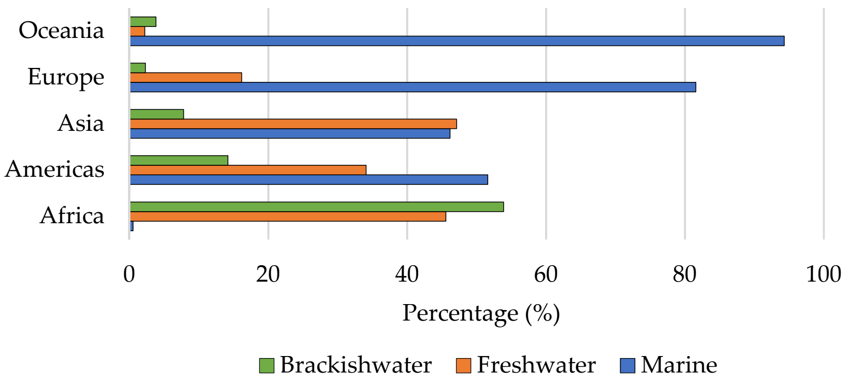

Figure 1. Seafood production of brackish, fresh and marine aquaculture: percentage of total production in 2018 by aquatic system in each continent. Data sources: FAO, 2020; FAOSTAT, 2022.

Asia has led aquaculture production worldwide for the past two decades. Inland aquaculture is the most common in the continent, representing about 65.5% of the continent's aquaculture production. Nonetheless, Asia is also, by far, the leader in marine and coastal aquaculture in the world, accounting, by 2018, for 25.1 million tonnes of seafood production, about 81.6% of the world's total marine and coastal aquaculture production [4,5]. Of the ten top aquaculture producing countries, five belong to the Asian continent: China (about 58% of global production), India (8.6%), Indonesia (6.6%), Vietnam (5%) and Bangladesh (about 3%). Of these, only Indonesia does not exceed 50% of aquaculture products of the total (capture fisheries and aquaculture) production, accounting for 43% of farmed products. China alone has produced, since 1991, more aquatic food than the rest of the world combined. The noticeable fall in China's production in the period 2016–2018, as briefly mentioned before, is explained by the country's recent adoption of strategies towards the improvement of the sector, searching for more sustainable and eco-sound practises, with higher efficiency in resource utilization, while focusing on the economic development of rural and other targeted poverty-stricken areas [4,5].

Chile alone contributes about a third of all aquaculture production in the Americas, being, as well, the eighth major producer in the world [4,5]. Chilean aquaculture focuses mainly on the production of both exotic and native species of finfish, such as salmon and meagre, and of molluscs, including red abalone, Japanese oyster and clams. These species are quite commonly farmed across the entire continent [12]. The United States of America stands out in terms of freshwater aquaculture production, with the farming of mainly catfish [13], conveying the United States of America the 14th place of major inland aquaculture producers worldwide [4,5]. Most countries in the Americas, apart from Chile, rely greatly on fishing efforts, but many have identified aquaculture as a potentially developing industry [4].

Africa is, of all five continents, the one experiencing the highest growth rates in aquatic animals' production since 2001. The highest rate was recorded in the period 2006–2010, of over 14% of growth compared to the previous period. Although the rate fell in subsequent years, in the period 2016–2018, the continent still registered a growth rate over 7%, above all other continents and the world average. Egypt, Nigeria and Uganda have contributed significantly to that growth, showing an ever-rising trend in aquaculture production, and contributing about 91% of total aquaculture products of the continent [4,5]. Egypt is, moreover, the sixth main producer worldwide. Almost all production (99%) in African countries is inland, in freshwater systems, focusing on the rearing of tilapia and African catfish. Mariculture contributes to the remaining 1% of production but is a sector to which greater importance has been given since the early 2010s [4,14,15].

The rapid rise in production in some African countries has been reported to be due to new investments, both public and private. Numerous small and medium scale enterprises (SMEs) of aquaculture have been setup, as well as large commercial enterprises of public support. According to some authors, the expansion of the aquaculture sector in some African countries is related to an overall growing interest and enthusiasm resultant from strong public support, foreign investment and import of expertise, as well as awareness raised by conferences and the implementation of the SPADA Program (Special Program for Aquaculture Development in Africa) [15,16].

The investment in the aquaculture sector consisted of the substitution of extensive and semi-intensive rearing systems by intensive pond rearing, which enabled a much higher density of animals, setup of hatchery and seed production, as well as feed production. Egypt has the highest number of hatchery and seed facilities [15–18], as well as all aquaculture feed being produced in the country [19–21]. A SWOT analysis conducted by Adeleke et al. (2021) [22] showed that both Egypt and Nigeria present well-developed aquaculture sectors, with thriving production and existence of market opportunities for product flow, associated with economic development.

Oceania is still quite underdeveloped in terms of aquaculture production [4,5]. The continent's contribution to global aquaculture in 2018 corresponded to 0.25%, consisting mainly of the rearing of salmonids, tuna and molluscs [4,5,22–27]. New Zealand is the major producing country, having produced, in 2018, over 104 thousand tonnes of farmed live weight. Australia followed, producing over 96 thousand tonnes. Aquaculture is developing in both countries; however, due to their extremely large Exclusive Economic Zone (EEZ; Australia's and New Zealand's EEZs are the third and fourth largest in the world), most aquatic animals' production is still coming from capture fisheries—only about 20% and 35% of aquatic products are from aquaculture in New Zealand and Australia, respectively. Despite the relatively low share of aquaculture contribution to aquatic animal's production in Australia, it is the country's fastest developing primary activity. Farming of aquatic animals in Australia focuses on the fattening stages of Southern Bluefin tuna in offshore cages, production of salmonids from initial stages (broodstock production inshore and offshore), prawn rearing in pond stations, mussels in ropes in marine waters, as well as on the production of abalone, oysters and other finfish (such as barramundi) []. New Zealand's aquaculture focuses mainly on the rearing of three species: green shell mussels, pacific oyster and Chinook salmon [23–28].

Aquaculture production in Europe in 2018 represented nearly 4% of the world's aquaculture production, with an output of about 3.1 million tonnes. Marine species make up most of the European aquaculture, accounting, by 2018, for about 83.5% of the continent's total production [4,29], thus leaving most European aquaculture to be carried out in marine and coastal environments. Fish and molluscs were the main groups reared, representing nearly the whole of the aquaculture production in Europe in 2018; the production of crustaceans and other aquatic animals represented a minor slice of Europe's production. Highly producing European countries focus mainly on the production of mariculture finfish species, such as coldwater salmonids, as is the case of Norway and the United Kingdom of Great Britain, and other marine species, such as seabass and seabream. Norway is the leading European country in aquaculture production, with an output of more than 50% of the total production in Europe by volume in 2018 (about 1.4 million tonnes of live weight) and the seventh main aquaculture producer worldwide [4,29,30]. Its production focuses mainly on the rearing of Atlantic salmon, which has been highly optimized to allow maximum production, adapting to rather rough conditions [31].

Spain, the United Kingdom and France were the following top European producers, accounting, together, for about 22.3% of the total European production in 2018 [30]. The Russian Federation falls in fifth place of major aquaculture producers in Europe—although the country extends through two continents, the authors have chosen to include the information as part of the European production data, similarly to the FAO. The Russian Federation focuses mainly on the production of freshwater species; it is particularly interesting to note the recent development of sturgeon aquaculture, which enabled the expansion of black caviar production, especially appealing to international markets [32]

Southern European countries—Spain, Italy, Greece, Turkey and Portugal—have a long history in aquaculture production and are responsible for the share of production of marine finfish, some freshwater fish and molluscs, which take the largest share of the production. Apart from Portugal, all other countries have generally optimized their rearing methods in the past few decades to maximize outputs, resorting to technological developments of intensive rearing methods [4,29,30,33–36].

Spain, France and Italy, although producing a number of commercially important marine, diadromous and freshwater finfish species, stand out from the rest of the European producing countries due to the highest share of each nation's total aquaculture production being mollusc farming [4,33–36]. Spanish share production of bivalves corresponded, in 2018, to 82.5% of total aquaculture production in the country, consisting mainly of mussels, oysters, clams and abalone [33,34]. France's share of bivalves was 78.2%, while Italy's was 65%. France focused 64% of its bivalves' production on oysters and nearly 34% in mussel production [35].

Greece and Turkey are the main European producers of European seabass and gilthead seabream, but these are also extremely important species in Spain, Italy and Portugal. Spain has the particularity of being the second major producer of Atlantic Bluefin tuna in the world, only preceded by Japan. Fish are captured in the Mediterranean after their migration for spawning, being subjected to a system of partial aquaculture, where fish are fed with highly nutritious and fatty feeds, to restore their high-quality fat content, and then be marketed to the whole world [29,30,33–36].

The contribution of each species' group for aquaculture production in the main European producing countries is represented in Figure 2.

Atlantic salmon (*Salmo salar*, Linnaeus 1758) was the main species reared, especially in Norway, which is the major salmon producer worldwide, accounting for 1.28 million tonnes produced in 2018, followed by the United Kingdom, the third main producer of the species in the world, with a production of 156 thousand tonnes in that year. Rainbow trout (*Oncorhynchus mykiss*, Walbaum 1792) was the second species most reared, with Norway and France as the main producers, followed by gilthead seabream (*Sparus aurata*, Linnaeus, 1758) and European seabass (*Dicentrarchus labrax*, Linnaeus 1758), both mainly produced by Turkey and Greece, occupying third and fourth places, respectively, as main species reared [29,30]. Concerning molluscs' production, mussels were the leader in terms of volume produced, corresponding to about two-thirds of molluscs' production in Europe, reared especially in Spain, followed by oyster production, with France as the main producing country [4,30].

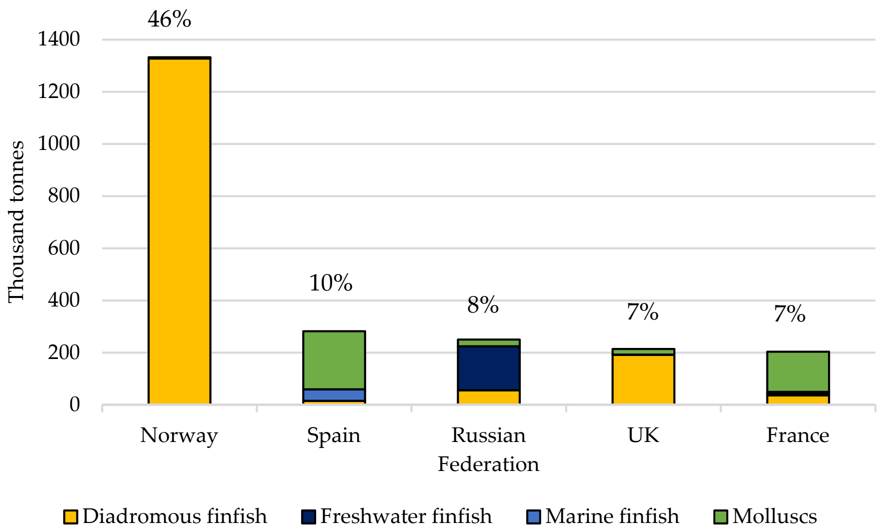

Figure 2. Aquaculture fish production of the main producing countries in Europe in terms of volume: percentage of European total aquaculture production in 2018. Values above each column represent the aquaculture production of each country in terms of percentage of the total European aquaculture production in 2018. Data source: FAO, 2020.

4. Aquaculture in Portugal

Portugal is a traditional fishing country, with a vast Exclusive Economic Zone (EEZ)—the 20th largest EEZ in the world—and a world-known tradition of high seafood consumption, both in terms of quantity and diversity of products [6–9]. Portuguese fish consumption per capita in 2018 was 61.5 kg, making Portugal the major consumer within the European Union member states and the third major consumer worldwide, preceded only by Korea and Norway [4,29,30]. A seasonal rise in fish consumption can also be associated with intense tourism during summer months, which demands a significant extra supply of such products. The combination of an extremely high demand for seafood, associated to geographic, abundance of marine resources and traditional reasons [37], result in the import of almost two-thirds of aquatic animals for human consumption. In 2018, Portugal imported 336.5 thousand tonnes of seafood for human consumption, corresponding almost entirely to finfish imports. Cod (including different species of the genus *Gadus*) is the main imported finfish, either fresh, frozen or sated, corresponding to 37% of total finfish imports [5]. The species does not exist in Portuguese waters but has remained a crucial ingredient in the country's eating habits, also encouraged by the high-quality nutritious profile of the fish, particularly its content in omega-3 fatty acids. In fact, until recent times, providing "cod liver oil" to children as an omega-3 fatty acids' supplement was very common in Portugal [38,39].

Although capture fisheries continue to play a vital role in the Portuguese economy, aquaculture has for a long time existed in the country.

Active rudimental aquaculture methods are thought to have been practiced for centuries in mainland Portugal, consisting essentially of the imprisonment of fish juveniles that used transitional systems as nursery areas in salt works and ponds in wetlands, letting them grow to be harvested when at a desirable size for consumption. Aquaculture in continental Portugal remained almost exclusively a familiar activity until around the beginning of the

20th century when it began to be regarded as a potential commercial activity that could contribute to the country's economy. Rainbow trout and freshwater species were the first to be farmed at a commercial level, but aquaculture in Portugal later evolved to the rearing of mainly marine species.

Despite the mentioned initial advances in aquaculture in Portugal, the activity had a slow development over the years, as fishing has always played an important role in the tradition and economy of the country [40]. Before the 1970s, 80% of fish aquaculture production in Portugal was of mullets; then, during the 1980s, the production was mostly of freshwater rainbow trout and bivalves in intertidal zones. The aquaculture of marine species did not experience true development until the 1990 decade, focusing at first on the rearing of gilthead seabream and European seabass, and more recently on the rearing of turbot (*Scophthalmus maximus*, Linnaeus 1758) and sole (*Solea* spp.) [41].

The development of aquaculture in Portugal took place after the country became a member state of the European Union (EU) in 1986 (at that time, named European Economic Commission). Because aquaculture was a key component of the EU's Blue Growth Agenda, community funds were attributed to Portugal as a member state for the development of the activity and the Portuguese Government itself invested in aquaculture development as well. The financial support given was intended for the development of research programmes that could enhance knowledge and know-how about aquatic animals' rearing, the construction of new and more suitable establishments, professional training of farmers and financial support to professional organizations [40–42]. Although Portuguese aquaculture experienced some development in the 1980s, the production decreased significantly in the 1990s, mainly due to a lack of criteria for the application of the available funds and issues in the production methods applied, leading to the unviability of many aquaculture units [42]. Nonetheless, despite some fluctuations in aquaculture production over the years, there has been a general rising trend in aquaculture production in Portugal, and true expansion in the past couple of years [6–9].

Portuguese aquaculture focuses on the production of marine fish and mollusc species, and most facilities are located on the country's mainland. Although intensive aquaculture has gained true importance recently, especially regarding fish production, most establishments are located and have further expanded in coastal systems, such as estuaries and coastal lagoons, along the country's mainland coastline. Aquaculture in the Portuguese archipelagos is yet poorly developed—only the Madeira archipelago presents aquaculture production, currently—although efforts are being made to expand the activity in the Madeira islands and promote the development of aquaculture production in the Azores archipelago [6–9].

The total marine aquaculture production in Portugal in 2018 was about 13.99 thousand tonnes, accounting for little over 0.50% of Europe's total aquaculture production [4–9,29]. Compared to other European countries of the EU, Portugal presents a much slower progress in aquaculture production and development, occupying 16th place in the rank of total aquaculture production amongst EU member states in 2018, contributing with less than 1% for the total aquaculture production in terms of volume in the EU [29,30].

The aquaculture of marine organisms in continental Portugal is essentially carried out in estuaries and wetlands along the coast, especially in the centre and south of the country, resorting to extensive and semi-intensive rearing methods. Although there is potential for the rearing of freshwater organisms, aquaculture activity in Portugal has focused essentially on the production of marine species since recent developments in aquaculture in the 20th century. In fact, freshwater aquaculture in Portugal represented 4.98% of the total aquaculture production in the country in 2018, 10.3% less than the freshwater aquaculture production registered in 2017. Aquaculture production in marine and estuarine systems accounted for the remaining 95% of the production [6–9]. The species reared in the mentioned systems, although marine species, frequently enter estuaries and other coastal systems at some point during their development, and are, thus, well-adapted to the environmental conditions. This fact, along with the availability of juveniles for the grow-out and the high market value of such species, makes them the first choices for aquaculture production in coastal systems in Portugal [40–44]. Although offshore farms are beginning to be implemented, there are still very few establishments operating, and the production from these facilities is yet notably low. As for intensive aquaculture systems, there were 23 establishments operating in Portugal in 2018, mostly aimed for the production of turbot and freshwater rainbow trout [11], which seem to be lowering in terms of number. Nonetheless, these facilities achieve much higher densities of organisms compared to semi-intensive and extensive systems. In 2011, the total aquaculture production in intensive systems surpassed the production in extensive systems due to a boost in the production of turbot. This species is reared essentially in intensive systems and, in 2011, its production accounted for 3197 tonnes alone, contributing to a total production of 3648 tonnes in intensive systems, while the total production in extensive systems (including fish and molluscs), was 3504 tonnes. In 2013 the production of turbot declined from 4406 to 2353 tonnes, causing the decrease in the volume of aquaculture products from intensive rearing systems, at the same time that mussel and oyster production grew significantly, enabling a new peak of production in extensive systems. From then on, extensive rearing production has risen every year, achieving a new country's maximum in 2018 [6–9].

Although the number of establishments using intensive systems of production is lower than those using extensive and semi-intensive systems, the comparison between the volume of production from each system shows that the production capacity is much greater in intensive systems.

Aquaculture production in marine and transitional waters in Portugal surpassed freshwater production for the first time in 1996. It has been the main contributor to the total aquaculture production in the country ever since, representing, in 2018, 95% of the total aquaculture production in Portugal, and reaching, by that year, its peak in production for the time frame issued.

Although intensive aquaculture has recently shown high production outputs for a small number of establishments, semi-intensive and extensive aquaculture are the most commonly used production methods in Portugal. These methods have been abandoned in most European countries while persevering in Portugal, and even experiencing developments in terms of techniques, rearing strategies and culture characteristics. Aquaculture production in the Portuguese archipelagos is carried out along the coast of the islands, in marine water, and, thus, the systems are not exactly transitional systems, compared to the reality on the mainland. Aquaculture production in transitional and marine waters (from offshore and intensive production capturing directly in marine waters) in mainland Portugal appears in official national publications as a whole, and, thus, the production referred to in the next section will provide the sum of the aquaculture production in both systems. The numbers will correspond almost entirely to transitional environments' production, as marine offshore production is essentially negligible, as afore mentioned.

4.1. Production in Coastal Systems

For administrative purposes, mainland Portugal may be divided into five main regions: North, Centre, Lisbon and Tagus Valley, Alentejo and Algarve; there are eight main areas for aquaculture in estuarine systems in Portugal, which are represented in Figure 3.

One of the most important rivers in Portugal is in the north of the country's mainland—the Douro river. However, its estuarine system is of small dimensions and not very suitable for the establishment of aquaculture farms. Thus, freshwater aquaculture is the most representative in this region, whereas production in transitional waters accounted for a mean of only 4% of the total aquaculture production in the region during the period between 1999 and 2018 [6–9].

At the centre of Portugal, there are two important areas for aquaculture in transitional waters: the Vouga estuary and the Mondego estuary.

The Vouga estuary forms a complex coastal lagoon with several natural ponds, consisting of an important wetland, known as Ria de Aveiro. This system covers about 11 ha and has been a Natura 2000 network site since 2014, listed as a Special Protection Area site under the Birds Directive. River Vouga runs through farmlands and urbanized areas, such as the city of Aveiro, during its course, being subjected to the input of many pollutants from runoff and domestic wastewater [45], and a highly monitored site in an effort to maintain its integrity and good status, nonetheless.

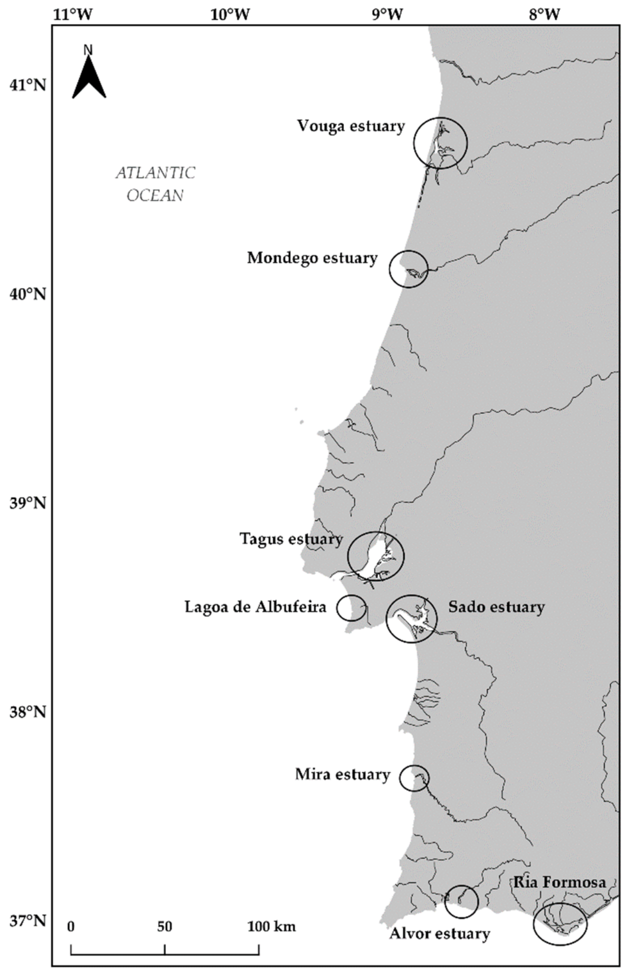

Figure 3. Main sites for aquaculture production in continental Portugal—circles mark the main sites for production in coastal systems.

The Mondego estuary has been, since 2005, a site under the Ramsar Convention on Wetlands. Along its course, the Mondego river runs through highly urbanized areas (such as the city of Coimbra), agricultural fields and industrialized areas, until reaching its 1600 ha estuary; the estuary itself is surrounded by urbanized (city of Figueira da Foz) and industrialized areas. The human pressures stated above contribute to the pollution of the river and the estuary, being the main sources of pollution urban wastewater (that is often only partially treated) and chemical products (e.g., pesticides, fertilizers, emerging contaminants) from agricultural water runoff and industrial sewage [46].

Both Ria de Aveiro and the Mondego estuary are very suitable for aquaculture in extensive and semi-intensive systems, which are known to have been practiced for a long time in these areas, taking advantage of non-operational salt works and modifying them for the production of fish in semi-intensive systems and molluscs in extensive systems. Aquaculture in transitional waters in the Centre region represented a mean of about 97% of the total aquaculture production in the region in the period between 1999 and 2018, accounting, in 2018, for 99.4% of the total aquaculture production in the region. Nonetheless, there are some concerns to be taken into consideration when operating with extensive and semi-intensive rearing methods. Fish farmers need to closely maintain the water quality of their tanks, given that, from time to time, greater amounts of pollutants may reach the estuary and fluctuations in the estuary water quality may potentially affect whole productions [46,47].

The Lisbon and Tagus Valley area comprises two main areas for aquaculture in brackish waters—the Tagus estuary and Lagoa de Albufeira—and a part of the Sado estuary as well. The Tagus estuary is the largest estuary in Portugal and one of the largest in Europe, with an area of approximately 32,000 ha, and about half of that area being a natural reserve. The city of Lisbon occupies the estuary's margins, in which numerous human activities operate, such as industries, fisheries and an important harbour, resulting in intense maritime traffic and other associated activities [48,49]. Aquaculture in the Tagus estuary focuses mainly on the production of oyster.

The Lagoa de Albufeira is a coastal lagoon with an area of 130 ha, with low water renewal and no connection to the ocean after the spring tides, after which a sand barrier is formed. This would isolate the lagoon from water renewal through ocean tides, if it were not for a tidal inlet, which is artificially opened to allow the renewal [50].

There is virtually no freshwater aquaculture production in the Lisbon and Tagus Valley area, which makes aquaculture in transitional waters the whole of the aquaculture production in the area, apart from the years 1999—with a production of 23 tonnes of freshwater organisms—and 2002, with a production of 3 tonnes of freshwater organisms [6–9].

The Sado estuary, comprised between the Lisbon and Tagus Valley and Alentejo regions, has been a natural reserve since 1980, extending for about 24,000 ha, being the second largest estuary in Portugal. Most of its area corresponds to the natural reserve (about 23,160 ha), still, the estuary is subjected to many anthropogenic pressures along its margins and thereabouts, namely several industries (especially on the northern margin), including paper, fertilizers, yeast, food and naval industries, the Setúbal harbour and related activities, the city of Setúbal and copper mines by which the Sado river runs through. Furthermore, the rice fields along the estuary's margins contribute to the input of pollutants and nutrients to the system. Despite all the pressures stated, the Sado estuary is still very suitable for salt and aquaculture productions [49,51].

The Alentejo region contains a small area aimed at aquaculture production (about 105 ha) in the Mira estuary; a low impacted system where the main pollution sources are from agriculture fields, tourist-related activities during the summer and urban waste from the small village of Vila Nova de Mil Fontes [52,53]. The total aquaculture production in Alentejo is in transitional waters, apart from the year 2006, with the production of 4 tonnes of freshwater products (from a total production of 757 tonnes) [10–13]. Although not being an area with great aquaculture production potential, the Alentejo region is one of the few regions in Portugal with natural occurrence of the Portuguese oyster (*Magallana angulata*) [40].

Algarve comprises two main areas for aquaculture—the Alvor estuary and Ria Formosa lagunar system. Ria Formosa is a coastal lagoon extending for about 16,300 ha, of which about 2000 ha are occupied by salt works and aquaculture ponds. This coastal lagoon is a Ramsar Convention on Wetlands and Natura 2000 network site and receives water input from small watercourses and from tidal exchanges with the Atlantic Ocean [54]. Although there are few industrial facilities along the lagoon's margins, they are heavily urbanized and include some areas of intensive agriculture and animal rearing, which are potential sources of pollution and high nutrient input to the basin (raising the risk for eutrophication of the lagoon) [55]. The basin is also profoundly modified from its natural structure due to coastal engineering, with the construction of artificial inlets in the western part of the lagoon, construction of dykes to retain freshwater from water streams (such as Ribeira de São Lourenço), two sewage treatment plants operating since 2000 and the Faro Airport constructed on the mudflats [55].

The Alvor estuary has been a Natura 2000 network site since 2006 and many activities have been developed on it, such as tourism, fishing and aquaculture production. The margins and adjacent land are quite urbanized and used for animal rearing, which may pose pollution threats to the estuary [56].

All the production in the Algarve region is on brackish and marine waters, and it is the region that most contributes to aquaculture production in Portugal, accounting for 53% of the total aquaculture production in the country in 2018 and for 56% of the production in Portugal in brackish and marine waters in the same year [11].

Although there are some hatchery establishments in Portugal, these have reduced to just a few units along the years—the highest recorded number of operating hatcheries occurred in 2003, with 12 working hatcheries, but has dropped considerably ever since, with only two operating in 2018. Thus grow-out units are the main aquaculture facility type in Portugal, whose number has been quite consistent over the years, with an average of 1430 operating facilities in the period 2000–2018. From 2017 to 2018, there was a drop in the number of grow-out units in the country—from 1431 to 1400—but this did not result in a drop in production; in turn, with the improvement in rearing techniques, aquaculture production followed a rising trend, as before stated.

4.2. Production Systems

The most common aquaculture production methods in coastal systems in Portugal, as briefly referred to, are extensive and semi-intensive systems, mainly aimed, and respectively, for the rearing of molluscs and fish.

For the time frame issued in the present work, extensive aquaculture production has oscillated somewhat over the years but has always maintained high production numbers, consisting almost exclusively of the rearing of molluscs. Production in semi-intensive systems, especially aimed for the production of fish, has suffered noticeable changes over the years: for example, the break in the production in semi-intensive systems between 2008 and 2011 was probably due to the conversion of semi-intensive facilities for the rearing of fish in units aimed for mollusc production in extensive systems [6–9], at the same time that intensive methods were preferred for the rearing of fish. The contribution of extensive, semi-intensive and intensive aquaculture rearing systems for aquaculture production in Portugal is shown in Figure 4.

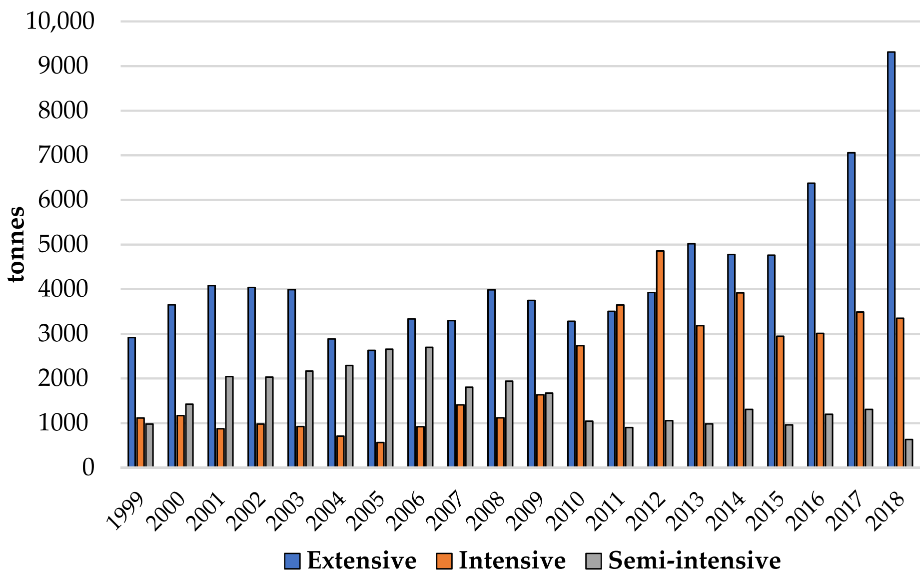

Figure 4. Aquaculture production of each of the three rearing systems in the period between 1999 and 2018. Data sources: INE 2000; INE 2002–2019.

4.3. Main Cultured Species

The aquaculture production in Portugal focuses essentially on the rearing of marine fish species, accounting for about 27.6% of the total national aquaculture production, and mollusc production, which accounted for about 67.2% of total national aquaculture production in 2018 [6–9]. Crustaceans are farmed in low quantities, having little expression in the country's aquaculture production and, thus, their contribution to aquaculture production in Portugal is included in the percentage of molluscs' production. Clams, oysters, turbot, mussels, gilthead seabream, rainbow trout and cockles were, by that order, the seven main species cultured in Portugal in 2018; of these, only trout is reared in freshwater systems [10]. Both turbot and trout are produced using intensive aquaculture methods, not being included in the production of coastal systems, and will not, therefore, be further discussed.

4.3.1. Fish Production in Transitional Systems

According to the most recent data, fish production in transitional systems in semi-intensive or extensive regimes in 2018 was about 511 tonnes, corresponding to 5% of the total aquaculture production in those conditions in Portugal that year [13]; the main farmed species was gilthead seabream, representing about 60.3% (308 tonnes) of the total fish production in that environment, followed by European seabass, which, together, accounted for 80.5% (508 tonnes) of the total fish production in coastal areas in semi-intensive regimes [13].

Gilthead seabream was the most cultured marine fish species in Portugal until 2010 when the production of turbot peaked. Seabream is a highly appreciated species in the Portuguese markets and is often reared in polycultures, especially with seabass, which has proven to be very effective [40]; since 2010, it has been the second most cultured species in the country, and the most cultured in coastal aquaculture. European seabass is one of the most appreciated fish species in Portugal and is essentially cultured in semi-intensive systems, usually in polycultures with gilthead seabream as mentioned above, being the third most cultured fish species in Portugal. The production numbers of both species over the years are represented in Figure 5.

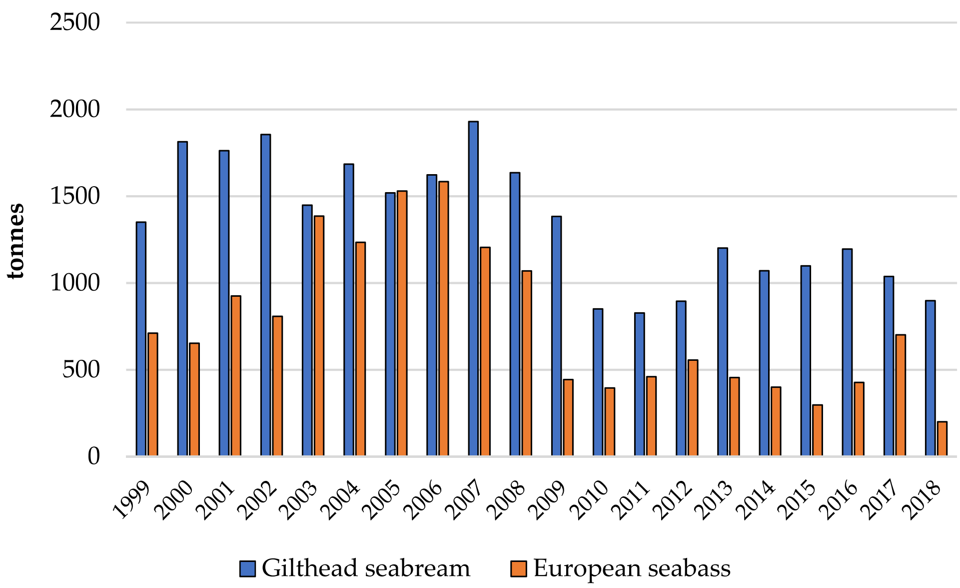

Figure 5. Total aquaculture production of the two main marine fish species cultured in brackish and marine waters in Portugal during the period from 1999 to 2018. Data sources: INE 2000; INE 2002–2019.

Semi-intensive aquaculture productions include a certain "natural" factor in the production and development of the organisms, as they are, although in captivity, still subjected to water conditions fluctuations or natural feed entering the tanks, which play a role in the fish quality and results in differences depending on the rearing origin. For instance, fish rearing cycles' durations differ according to the geographical site: water temperature is generally lower in the central regions of the country when compared to southern farms, with harvesting cycles taking longer at the centre of continental Portugal. These last for approximately 24 to 26 months (from the juvenile stage, about 10 g, to the marketable size), whereas, in the southern regions, cycles may take about 14 to 20 months to be completed [43]. In semi-intensive systems, the quality of the estuarine water used is one of the most pressing parameters to be taken into account by the farmer, as well as the nutrient control, given that fish do not feed only on the food given by the farmer but also on organisms and other organic matter brought into the rearing tanks by the river flow and ocean tides. Therefore, these parameters must be carefully watched to avoid the loss of high densities of fish. Nonetheless, feeding on natural prey varies the nutritional profile of these fish, which may come as an advantage for the consumer.

Extensive production of fish is, at present, neglectable, with no records of the volume of production in such regimes. This kind of fish rearing was practiced essentially in inactive salt works, beginning, probably, when the salt market started to struggle with some difficulties [43]. This rearing system is not as productive for fish as semi-intensive or intensive systems as only very low densities of individuals can be achieved.

4.3.2. Mollusc Production in Transitional Systems

Bivalve molluscs represent a little over 67% of the total aquaculture production in Portugal [13]. The most produced species is the clam (*Ruditapes decussatus*, Linnaeus 1758), accounting for about 42.2% of the total mollusc production, followed by mussels (*Mytilus* spp.) and oysters (combined production of Portuguese oyster *Crassostrea angulata* Lamarck, 1819, European flat oyster *Ostrea edulis* Linnaeus, 1758 and Pacific cupped oyster *Magallana gigas* Thunberg, 1793). The production of the main mollusc species produced in the time frame issued is represented in Figure 6.

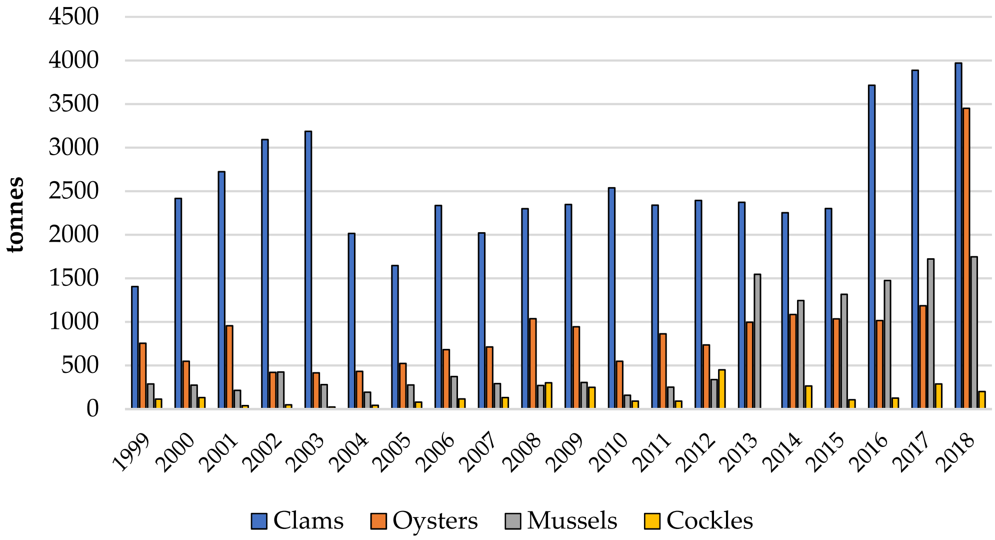

Figure 6. Total aquaculture production in transitional waters of the four main cultured mollusc species in Portugal during the period from 1999 to 2018. Data sources: INE 2000; INE 2002–2020.

The production of molluscs in continental Portugal is mainly carried out in extensive systems, although there is mollusc production in semi-intensive systems as well. Extensive rearing of molluscs is essentially carried out in parks, in their natural substrate (mud or sand) [43] or in ropes (mainly for mussels production).

The production of molluscs in semi-intensive systems occurred occasionally over the time frame issued but in quite low quantities. The most expressive production in such systems was the production of Pacific cupped oyster in 2006 with 250 tonnes produced, and the production of 125 tonnes in 2014; clams also registered a considerable production of 88.8 tonnes in 2006 and 63.4 tonnes in 2010. However, for the remaining time, mollusc production in semi-intensive systems was nearly imperceptible [6–9]. Clam is the main reared mollusc species in Portugal in brackish waters and the main produced species in the country. Clams are reared in parks in intertidal zones [7], in extensive systems, essentially in the south of continental Portugal. Clam production grew continuously from 1999 to 2003, with the highest growth registered between 1999 and 2000, where a production of around 1404 tonnes in 1999 rose to a production of 2417 tonnes in the following year. The production of these organisms peaked in 2003, with 3186 tonnes produced, but dropped in following years, almost matching the production values of the year 1999. Clam production remained, until 2015, rather regular, with a rough average of a little more than 2300 tonnes produced each year. The production of these organisms recovered in 2016, presenting a rising trend ever since, as can be seen in Figure 6 [6–9].

The production of mussels remained discrete from 1999 to 2012, revealing a peak from 338 tonnes in 2012 to 1.5 thousand tonnes in 2013, maintaining the same production amount in 2016, being the second most produced mollusc in Portugal. Although most of the aquaculture of mussels in Portugal uses long lines, in extensive systems, there was some production in intensive systems in 2009 (30 tonnes) and in 2011 (62.5 tonnes) [6–9].

By the end of the 19th century, the Portuguese oyster was the most appreciated delicacy demanded by the European market (especially France), which led to an increase in the species' capture in the Tagus estuary during that period, reaching, during the 1930s, exportations of 13 thousand tonnes per year [43]. It was the only oyster species being reared in continental Portugal until 2004 when its production dropped abruptly and was replaced by the production of the Pacific oyster. The Portuguese oyster production recovered in 2009 and has been growing ever since [6–9]. Oysters are usually reared in net bags placed on the substrate, which may subject them to predation; the culture in long lines and floating devices, used mainly in Algarve, protects animals against non-swimming predators, as the organisms are suspended in the water column [43].

The cockle's, *Cerastoderma edule*, Linnaeus 1758, production has fluctuated during the time frame issued, maintaining a low production between 2001 and 2005, rising in 2006 and reaching a production of about 300 tonnes in 2008, the second biggest production of cockle in the period covered by the present work. The greatest production of cockle until the present time was reached in 2012, accounting for 449.2 tonnes produced. However, there was no production of this species in 2013. Since then, the production of the species has been quite unstable. Cockle production is carried out essentially in parks, using extensive systems [6–9,43].

Portuguese aquaculture products have for a long time been introduced in national markets; however, due to market choices in importing high quantities of seafood, which are also produced in Portugal, from other major producing countries, such as Greece and Turkey, as above mentioned, this imbalanced somewhat the local products' flow. It was only recently that a more serious effort was taken to stimulate the purchase of locally farmed fish, which has also impacted the choices of large commercial centres in terms of the products offered to consumers. Moreover, the overarching stress on social responsibility towards more sustainable consumption has also helped to push consumption of locally produced goods.

It is worth mentioning, however, that seafood in Portugal is commonly expensive for the population on the minimum and average wage (which make up most of the Portuguese population) [11,57]. This raises a question on the ability of the Portuguese population to access healthy food environments and local production flow, as many people end up having to opt for cheaper, imported seafood. The price of Portuguese farmed seafood in coastal systems using semi-intensive and extensive systems is presented in Table 1. This table includes values from 2018 and 2019, as more recent data are easily accessible when it comes to market values.

Table 1. Average national prices (EUR/kg) of Portuguese coastal systems' aquaculture products for human consumption in 2018 and 2019.

		Value	
	Product	**2018**	**2019**
Fish	Meagre	11.12	5.67
	Gilthead seabream	5.85	5.43
	European seabass	8.81	7.31
	Sole	12.85	11.02
	Eel	6.00	9.00
Molluscs	Clams	12.88	18.71
	Cockles	0.52	1.05
	Mussels	0.77	0.74
	Oysters	4.26	10.65

4.4. Portuguese Aquaculture Products' Market—Exportations and Main Consumers Worldwide

Due to the lack of available information, a comprehensive overview of the exact countries to which Portuguese farmed products are exported to was not possible. Rather, fish export information related to the destination is provided as the sum of capture and farmed goods. Major exportation destinations include Spain, Italy and France in Europe and the United States of America outside Europe [39,58].

Nonetheless, information on the volume and value of exports of aquaculture products per se are available, accounting, in 2018, for a total of 2967 tonnes, valuing over 23 million euros. Marine species were the most exported, corresponding almost entirely to turbot (2640 tonnes), valuing 21.4 million euros; bivalve exports corresponded to only 213 tonnes, valuing 612 thousand euros, consisting mainly of oysters and mussels [9].

The availability of detailed information regarding Portuguese aquaculture products' exports via the institutions responsible for those records could be interesting for a further characterization of the development of the aquaculture sector in Portugal.

5. Discussion

Asymmetries in countries' aquaculture production across the globe have remained rather unchanged throughout the years, despite some examples of rapid and effective development of the sector, as in the case of Egypt that went from being a low producing country with an output of 62 thousand tonnes in 1990 to a production of 1.56 million tonnes in 2018, putting Egypt in sixth place of the ranking of major aquaculture producers globally [4,5,20,22]. It is expected that larger countries produce larger volumes of seafood; however, the share of farmed products of different nations is truly unbalanced. While major producing countries have always contributed the most for the input of farmed goods in international markets, others have relied on imports of such products, not having developed the sector to meet each population's demands.

As mentioned before, exemplified by the cases of some African countries and Portugal itself and extensible to all other major producing countries, many countries report the importance of governmental and institutional contributions to the set of development strategies and planning to boost the sector development and establishment over time, considering each nation's geographical, social and economic factors, to meet its needs. Indeed, the aquaculture sector may have been the last to be established worldwide as a significative contributor for countries' economies, and its sustainability as a relevant sector has only recently been approached at a global level. The activity has proven to be, overall, quite profitable, as well as enabling the creation of new job positions, having contributed to reducing unemployment rates quite significantly in some countries [4,59,60].

However, historically, the great expansion of production sectors usually comes hand-in-hand with underlining environmental issues. Aquaculture facilities pose different issues regarding the rearing method (if intensive, semi-intensive or extensive). Overall, there is the risk of high nutrient loads, or of other chemicals (such as antibiotics), from non-treated wastewaters to surrounding environments, which can be particularly significant in fed semi-intensive rearing regimes. The transition of single-species aquaculture facilities to integrated multi-trophic aquaculture (IMTA) is being adopted and tested in some parts of the world, especially in major producing countries looking for greener alternatives for their production [4,61]. These systems provide, as well as ecological benefits, added value to the profitability of land use, as organisms of different trophic levels may be produced at the same time. The use of land (or water, in the case of offshore production) is another major issue posed by aquaculture establishments, especially regarding semi-intensive and extensive practices. Facilities have implications in the integrity of ecosystems, land and water utilization, often competing with other sectors [62], and they impact the natural state of wild communities and irreversibly change habitats. In some countries, such as Portugal, for example, the conversion of inoperative salt pans somewhat dilutes this issue, as land already altered is being reused and rehabilitated, only for a different purpose.

Moreover, the mass production of highly desired species by major producing countries has, in the recent years, resulted in the saturation of national and international markets, causing significant drops in the prices of such species, even in small-producing countries, affecting regional economies with societal consequences, not to mention the considerable amount of waste produced [4]. As briefly mentioned before, the high input of cheaper gilthead seabream and European seabass produced by Greece and Turkey into Portuguese markets imbalanced the local consumption of those products, which are the two main finfish species reared in the country. All these constraints must be taken in consideration when evaluating the benefits of developing aquaculture practices.

In addition to the overall accepted benefit of aquaculture of releasing the pressure over overexploited wild stocks to meet fish market demands, aquaculture ought to develop as a means to promote healthier nutrition environments. That is, as well as fulfilling its most immediate role of feeding populations worldwide, which is still brutally asymmetrical throughout the world –, aquaculture also potentiates the provision and accessibility to high-quality, accessible-to-all food due to an overall lowering in prices when compared to captured products and the selection of high-quality species of a food source that is, in general, already considered healthy [63]. This involves the selection of species with rich and healthy nutritional profiles and the choice of high-quality feeds (when it comes to fed production), preferably of local production, as well as political options towards the setting of achievable prices, while properly compensating producers. All in all, the aim is an integrated economic strategy that enables the production and consumption of locally produced goods that benefits countries economically, socially and environmentally.

Last (but not at all least), there is also the necessity to determine whether further development of aquaculture practices benefit every reality—hence the need for a country-scale strategy definition for the practice.

Whichever solution is found—more intensive aquaculture for higher food production, or the redefinition of capture fisheries to eco-sound practices to preserve small-scale fishing—the extremely high demands of seafood markets worldwide, particularly concentrated in the Northern hemisphere, pose a serious sustainability issue at many levels. Aquaculture expansion, regardless of efforts to turn to more sustainable practises, will always take up land and water resources, result in more or less controlled nutrients and other chemicals' loads to surrounding water bodies and the overarching production of food that is asymmetrically distributed across the globe, exceeding the need (and producing waste) in a few places, but lacking in a lot more.

Human diets in the commonly called developed countries usually exceed the amount of nutrients needed per day, but continue demanding exceeding food, often presenting higher offer than consumption. This generates great deals of waste from non-eaten products, a reality that urgently needs to be reassessed and redesigned. The continuity of the overdemand and waste of food products is reprehensible, especially as it is an issue widely identified and discussed. However, such habits continue to negatively impact the access to food in less developed areas. Strategies must be defined to encourage eating habits that are more environmentally sound, although it may mean lower profits in expanding industries, such as aquaculture. On the other hand, action must be taken at governmental and institutional levels to overtake deepening asymmetries regarding food accessibility between so-called developed and developing countries, especially concerning the balancing of food distribution, which will necessarily reduce food waste, at the same time that steps are taken towards lowering malnutrition across the globe. Although this theme has for a long time been discussed, being one of the main concerns declared by the United Nations (UN) and associated to many Sustainable Development Goals set in the UN's 2030 Agenda [64], it remains one of the most serious social calamities of our world, at the expense of fast-growing international markets.

6. Conclusions

Aquaculture continues to develop worldwide, with some countries and regions presenting truly fast expansions, turning the sector into a relevant contributor to national economies. However, potential issues posed by aquaculture, either environmentally or in a socio-economic perspective, have been somewhat overlooked, and need to be reassessed.

As one of the leading fish consumers per capita in the world, it would be expected that Portugal had already further developed aquaculture practices as a means of matching the market demand and complement capture fisheries, but production is still far from matching such needs. Moreover, the most appreciated fish by the Portuguese population—cod—does not occur in the Portuguese fishing area, and cannot, either, be farmed (at least for the time being), making imports unavoidable.

Most of the aquaculture facilities in Portugal focus on the production of marine fish and bivalve molluscs, essentially carried out in estuaries and coastal lagoons, in extensive and semi-intensive systems. Although facilities using intensive production systems are more efficient in the rearing of organisms and could attain greater production numbers, they are only used for a small number of fish species.

In continental Portugal, aquaculture production in coastal systems reached a little over 13 thousand tonnes in 2018, the greatest production for the period issued—from 1999 to 2018—representing about 95% of the country's total aquaculture production.

Offshore farming in Portugal is in development but, for the present time, it resorts to a few cages and longline systems for bivalve molluscs' production on the south coast of Algarve, operating since 2008.

Fish production in semi-intensive systems accounts for only about 5% of the total aquaculture in coastal systems in continental Portugal and focuses mainly on the production of gilthead seabream and European seabass, mostly reared in the centre and south of continental Portugal. Most marine fish production is currently being carried out in intensive systems; however, the development of semi-intensive facilities and the growth in production in some of these systems (and their introduction in the markets) deserves to be mentioned as it is argued that this mean of production retains fish characteristics closer to those found in wild caught fish.

Mollusc production represented about 67% of total aquaculture production in 2018, focusing on the rearing of clams, oysters and mussels, almost exclusively reared in extensive regimes in coastal areas.

Although a small producing country, ranking 20th in terms of aquaculture volume production in Europe, aquaculture production in Portugal has been showing a rising trend over the years, and research about aquaculture's methodologies and best practices is being developed. It is a sector that is given greater importance every year and should continue to expand and develop throughout the following years.

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