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Review

Adriatic Sea Fishery Product Safety and Prospectives in Relation to Climate Change

Edmond Hala [1] and Rigers Bakiu [1,2,*]

[1] Department of Aquaculture and Fisheries, Faculty of Agriculture and Environment, Agricultural University of Tirana, 1000 Tirana, Albania; hiedmo@ubt.edu.al
[2] Albanian Center for Environmental Protection and Sustainable Development, 1000 Tirana, Albania
* Correspondence: rigers.bakiu@ubt.edu.al

Abstract: This bibliographic study addresses key aspects related to fishing, product safety, and climate change in the Adriatic Sea region. The examination of product safety focuses on the assessment of contaminants originating from human activities such as industry, mining, agriculture, and household waste disposal. The contamination of the aquatic environment has emerged as a pressing global concern, extending to the Adriatic basin. Aquatic organisms, including fish, are prone to accumulating pollutants directly from polluted water sources and indirectly through the food web. The bio-accumulation of potentially hazardous substances, particularly heavy metals, pesticides, PCBs, PAHs, and antibiotic resistance in aquatic organisms, poses a significant threat to human health. Climate change effects will deplete our seafood supply in terms of quantity and safety owing to negative consequences such as higher levels of pollution, parasites, viruses, infections, acidification, and toxicities such as shellfish poisoning. Global food safety strategies should be developed to reduce greenhouse gas emissions and promote environmentally friendly technology, which indirectly affects seafood quality and microbiological safety, especially for the Adriatic Sea, which is part of the Mediterranean Sea, characterized by the most polluted waters in the world.

Keywords: fishery product safety; climate change; fishery management; Adriatic Sea; Mediterranean Sea

Key Contribution: Actually, the flora and fauna of the Adriatic Sea is the result of numerous geological, geographical, climatic, and biological processes that occur during its formation. Its aquatic environment pollution is becoming a concern for the human health of the populations living in the coastal areas of the Adriatic basin because the bio-accumulation of potentially hazardous substances, particularly heavy metals, pesticides, PCBs, PAHs, and antibiotic resistance in aquatic organisms, poses a significant threat to human health. In the context of climate change effects, the level of threat impact will significantly increase, as it will be integrated into consequences deriving from climate change. New food safety strategies should be developed to affect seafood quality and microbiological safety in the context of the Adriatic basin.

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1. Fishery Production and Management

1.1. Adriatic Sea Specificities

The Adriatic Sea is recognized as a hydrologically independent subsystem of the Mediterranean Sea [1]. The northernmost part of the Mediterranean Sea, excluding the Black Sea, is typically divided into three subareas: North Adriatic, Central Adriatic, and South Adriatic (Figure 1). The east and west coasts of the Adriatic Sea differ significantly; the former is characterized by high, rocky terrain with numerous islands, while the latter is flat and alluvial, featuring raised terraces in specific regions [2]. The east coast, due to its many islands, boasts a diverse coastal habitat. The depth of the sea decreases from south to north, with the northern Adriatic never exceeding 100 m in depth. The deepest point in the Central Adriatic region is 273 m in the Jabuka/Pomo Pit, while the South Adriatic reaches its maximum depth in the Adriatic Sea (South Adriatic Pit) at 1233 m. On average, the depth of the Adriatic basin is approximately 252 m [1].

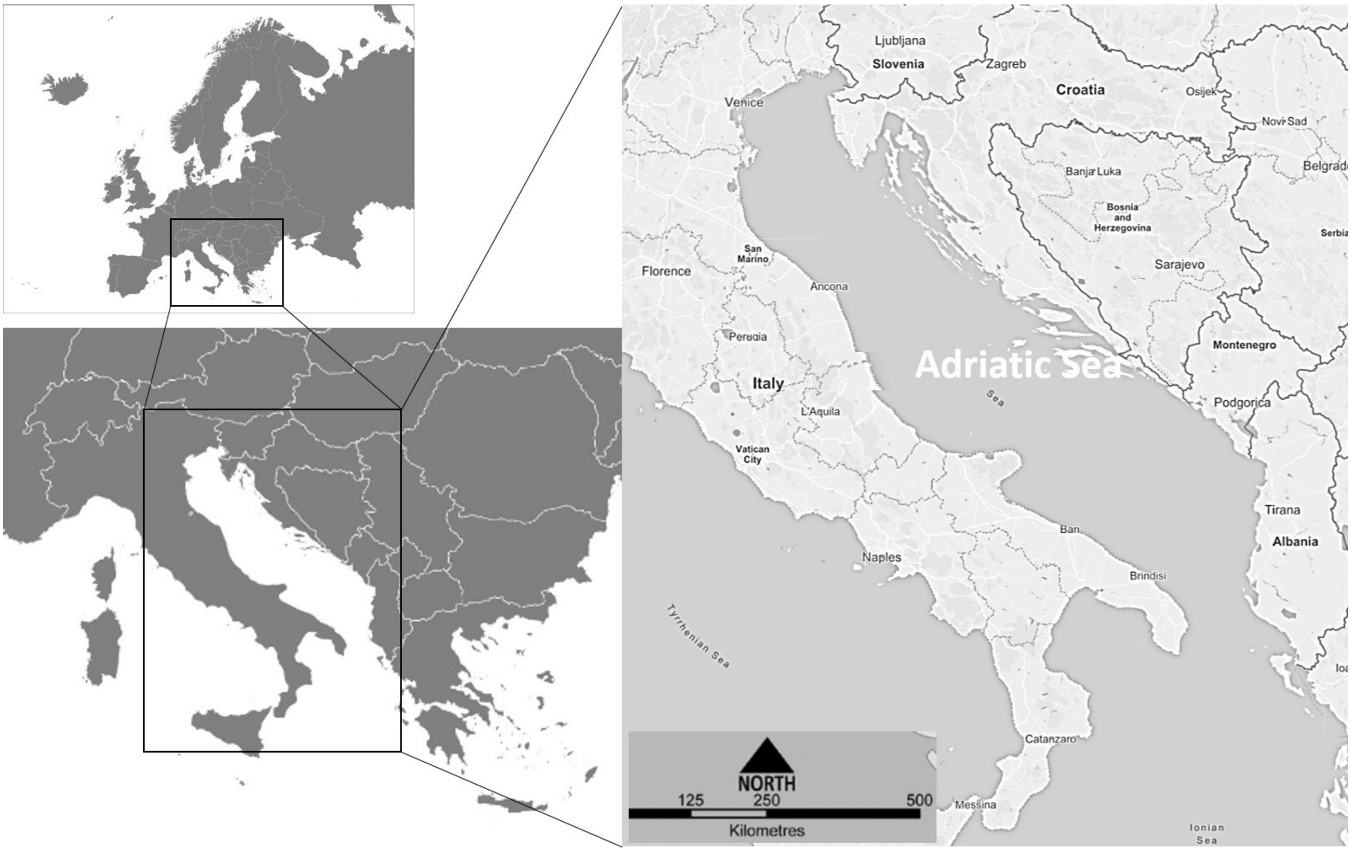

Figure 1. Location of the Adrifatic Sea in the European map.

The thermohaline characteristics of the Adriatic Sea are primarily determined by various factors such as sea–air interactions, river discharge, mixing, flow, water exchange through the Otranto Strait, and the general topography of the basin [1]. In terms of surface water temperatures, the southern region experiences temperatures around 18 °C, while the northern Adriatic Sea can reach up to 25 °C. Extreme surface temperatures can range from 6 °C to 29 °C. Even in the deepest layers, average temperatures typically exceed 10 °C. During winter, the southern Adriatic Sea tends to be 8–10 °C warmer than the central and northern regions. In other seasons, the horizontal temperature profile is more uniform. Generally, open seas tend to be warmer compared to coastal waters [3].

The salinity content in the Adriatic Sea is relatively high and exhibits considerable variation. The highest salinity levels are found in the southern Adriatic region (ranging from 38.4 to 38.9), particularly in the middle layer. Generally, salinity decreases from south to north and from the open ocean to the coast. The northern and western parts of the Adriatic Sea are more influenced by river flooding, primarily from the Po River. This influx of freshwater affects the water cycle through upwelling and has an impact on the ecosystem dynamics due to the introduction of significant amounts of nutrients [4]. The currents within the Adriatic Sea are highly intricate and consist of multiple layers (surface, intermediate, and bottom layers). These currents are influenced by the overall circulation system of the Mediterranean Sea. In essence, the surface circulation in the Adriatic Sea can be described as a large-scale meandering with a northerly flow along the east coast and a southerly flow (return) along the west coast [5]. However, the specific geomorphology and significant seasonal variations add complexity to the hydro-biological system of the Adriatic Sea, making it a challenging yet fascinating area of study, as highlighted by Dragičević et al. [1].

The Bimodal Oscillating System (BiOS) mechanism is a crucial hydrological feature that connects the Adriatic Sea with the rest of the Mediterranean through the Ionian Sea. This mechanism plays a role in altering the flow pattern of the North Ionian Gyre (NIG) from a cyclonic direction to an anticyclonic direction and vice versa over a period of decades [6]. This process allows water to flow into the Adriatic Sea from both the Ionian Sea and the central Mediterranean Sea in response to low- or high-pressure systems. Additionally, the BiOS mechanism has an impact on the biodiversity of the Adriatic Sea, as it influences the abundance and appearance of certain organisms. The presence of these organisms can indicate the occurrence of a BiOS regime, which involves the influx of water from either the Western Mediterranean/Atlantic or the Eastern Mediterranean [7].

The theory of "Adriatic Ingressions", which was initially proposed by Buljan in 1953, has been associated with features influenced by the BiOS mechanism [8]. This theory has been updated with the introduction of the BiOS mechanism [1]. The presence of various thermotolerant species in the Adriatic Sea has also been linked to the phenomenon of "Adriatic Ingressions" [9]. The influx of warmer, more nutritious, and saline Ionian waters not only contributes to the presence of rare and exotic species in the Adriatic basin but also has a significant impact on the overall biodiversity of the Adriatic Sea. The current flora and fauna of the Adriatic Sea are the result of various geological, geographical, climatic, and biological processes that have occurred during its formation [1].

1.2. Fishery Production

The countries bordering the Adriatic Sea are divided into two parts. Italy represents the western part, while Slovenia, Croatia, Montenegro, and Albania represent the eastern part, from north to south. However, due to its limited coastline, Bosnia and Herzegovina will not be considered in this review. In terms of fishing fleet composition, the majority (77.9%) consists of small-scale fishing vessels in the Adriatic Sea. The remaining portion is made up of trawlers and beam-trawlers (12.9%) and purse seiners and pelagic trawlers (2.8%) [10].

When it comes to production, the "Purse seiners and pelagic trawlers" group is responsible for the highest percentage of landings in the Adriatic Sea, accounting for 58.8%. Trawlers and beam-trawlers contribute 19.7% of landings, while small-scale fishing vessels make a minimal contribution of 7.4% [10]. In terms of average annual landings, Croatia and Italy are the leading countries, with 65,465 ton (45%) and 73,924 tonnes (50.9%), respectively [10]. Albania holds the third position for the time period of 2020–2021, with 5235 tonnes (3.6%), while the remaining countries collectively account for 7735 tonnes (0.5%) [10].

The Adriatic Sea is dominated by two main species in terms of landings. The European anchovy (*Engraulis encrasicolus*) contributes 20.1% of total landings, amounting to 24,341 tonnes, while the sardine (*Sardina pilchardus*) accounts for 47.4% with 57,890 tonnes [10]. Other notable species include the spottail mantis squillid (*Squilla mantis*) with 2624 tonnes and the European hake (*Merluccius merluccius*) with 3550 tonnes [10]. It is worth mentioning that the landings of European hake have declined in recent years across the Mediterranean basin. In 1994, the landings were recorded at 1052,394 tonnes, but by 2021, they had decreased to 17,824 tonnes [10]. Some stocks under management plans have shown a more significant decrease in fishing pressure compared to the average. An important case to highlight is the remarkable 77 percent decline in common sole numbers in the Adriatic Sea since 2011 [10].

Regarding aquaculture production, Italy is one of the largest producers not only in the Adriatic basin but also throughout the Mediterranean basin. It stands as the fourth largest producer, trailing behind Greece [10,11]. However, Italy is categorized alongside other countries in the Adriatic basin, such as Montenegro and Slovenia, which experienced a decline in production from 2018 to 2021 [10]. On the other hand, Albania witnessed the highest growth rates between 2018 and 2019 and 2020 and 2021, with a remarkable increase in production of 59.3 percent (+2652 tons). Croatia also demonstrated a commendable growth rate of 22.4 percent (+3826 tons) [10]. In line with the entire Mediterranean basin, the primary species cultivated in the Adriatic basin include gilthead seabream (*Sparus aurata*), European seabass (*Dicentrarchus labrax*), Mediterranean mussel (*Mytilus galloprovincialis*), meagre (*Argyrosomus regius*), Atlantic Bluefin tuna (*Thunnus thynnus*), mullets (*Mugilidae*), and rainbow trout (*Oncorhynchus mykiss*) [10,11].

1.3. Fishery Management

The aim of this section is to provide a thorough analysis of the key regulations that have had and continue to have an impact on the small pelagic and demersal fisheries in the Adriatic region [12–14], though there are several multilateral environmental agreements available, which indirectly impact fisheries in almost all the countries of the Adriatic basin [15].

As a member of the European Economic Community (EEC) and later the European Community (which was later incorporated into the European Union), both Italy and Slovenia are legally bound to comply with the regulations established by the EU. These regulations grant Member States the authority to implement measures for the conservation of fish stocks within their waters as long as these measures are at least as strict as the existing EU regulations [12,16].

In 2001, Croatia took a significant step by signing the Stability and Association Agreement with the European Union. This agreement solidified Croatia's commitment to adhere to the Common Fisheries Policy (CFP) and alignment with the EU's binding regulations. However, despite this commitment, Croatia has been undertaking a fleet renewal initiative since 2004, which involved the construction of new fishing vessels and an overall increase in the capacity of its fleet [12,16]. Additionally, the Croatian government aimed to establish an Ecological Fisheries Protection Zone (EFPZ), which could potentially contradict the CFP agreement and result in the exclusion of EU fishing activities within the Croatian zone. After several years of discussion and negotiation, the EFPZ was approved and came into effect in 2008, with certain exemptions granted to EU vessels [11]. Although there have been improvements in recent years, particularly after Croatia's accession to the EU, the country's fisheries sector continues to be heavily influenced by domestic politics and circumstances [17,18].

Italy's national regulatory framework, in conjunction with EU regulations, has historically played a crucial role in effectively managing various aspects of fishing. This includes the careful control of the number of licenses granted, the specific attributes of fishing gear, the technological aspects of fishing vessels, and the limitations imposed in terms of space and time. Similarly, Croatia has also adopted a similar approach to fisheries management. The main legislative instruments in Croatia were initially drafted in 2000 and 2006 and have since been further developed to address important aspects such as fishing gear, time and space limitations, and species protection. These regulations have been designed to regulate fishing areas by considering factors such as fishing effort and catch capacity [19]. In line with these legislations and in accordance with the directives outlined in the reformed (CFP), recent measures have been implemented to address the concerns raised by the scientific community and the fishing industry itself. These measures specifically target both small pelagic and demersal fisheries, aiming to ensure sustainable fishing practices and the long-term preservation of marine resources [12,20].

Several measures recommended by GFCM have been implemented, including a reduction in the number of fishing days for anchovy and sardine to a maximum of 144 days. Additionally, Italy has closed a six-mile strip along the entire coast for 6 months from 1 July to 31 December, while Croatia has closed the inner seas for 6 months in 2016 and 2017 from 1 April to 30 September. Furthermore, there are extra temporal closures for sardines between 1 October and 31 March and for anchovy between 1 April and 30 September. Catch and fishing capacity limits have also been imposed for both species [12,15]. Moreover, the Pomo/Jabuka Pit, which serves as a crucial nursery area for European hake (*Merluccius merluccius*) and harbors a resident population of Norway lobster (*Nephrops norvegicus*) [21], was subjected to a 15-month prohibition on trawl fishing during the period of 2015/2016 [12]. Since October 2016, access to this area has been granted to a restricted number of authorized bottom trawlers, while bottom long-liners remain prohibited. This regulatory action primarily impacted Italian fishing vessels and was accompanied by the implementation of a specialized monitoring program initiated in 2015 and currently conducted on an annual basis [22].

The management of marine stock in the Mediterranean Sea involves several key entities. These entities can be categorized into four main groups. Firstly, there is the Food and Agriculture Organization (FAO), which has its own Regional Fisheries Management organization (RFMO) known as the GFCM. Additionally, the FAO also has its Scientific Advisory Committee on Fisheries (SAC) and supports various regional projects [10]. Secondly, the European Commission (EC) and its affiliated bodies, such as the Scientific, Technical and Economic Committee for Fisheries (STECF) and the Joint Research Centre (JRC), play a significant role in the management of marine stock. Thirdly, the national authorities of the Mediterranean countries contribute to the management efforts. Lastly, the fisheries associations, under the coordination of the MEDiterranean Advisory Council (MEDAC), also play a crucial role in the management of marine stock in the region [12,15].

Established in 1949, the General Fisheries Commission for the Mediterranean (GFCM) serves as the official Regional Fisheries Management Organization (RFMO) for the Mediterranean and Black Sea regions, operating under the umbrella of the Food and Agriculture Organization (FAO). The primary goal of the GFCM has been to advance the sustainable development, conservation, and responsible governance of marine fishery resources in these areas, fostering a platform for dialogue among nations from both Europe and beyond [11]. In 1997, the GFCM transitioned into a Commission, assuming a pivotal role in shaping fishery policies within the region. It possesses the authority to issue mandatory recommendations concerning the safeguarding and regulation of fisheries activities within its jurisdiction, with these recommendations carrying legal weight upon notification to individual Member States [10–12]. The GFCM relies on scientific advice provided by the SAC to offer impartial recommendations on the technical and scientific aspects of decisions related to fishery conservation and management. The Directorate-General for Maritime Affairs and Fisheries, also known as DG-MARE, serves as the primary entity within the European Commission responsible for executing the CFP and the Integrated Maritime Policy [16]. DG-MARE obtains scientific guidance for the implementation of the CFP from the International Council for the Exploration of the Sea (ICES), which focuses on Northern Europe, and the Scientific, Technical and Economic Committee for Fisheries (STECF), an EC body designated as the scientific advisory body for the EU and operates across all EU-controlled regions, including the Mediterranean [11,16].

The primary responsibility for implementing the regulations set by the GFCM and the EU lies with the national authorities, including ministries and port authorities. In Italy, Croatia, Albania, Slovenia, and Montenegro, the Ministry of Agriculture's fisheries directorates are entrusted with the task of executing these regulations [15,19]. These directorates serve as the competent authorities for Monitoring, Control, and Surveillance (MCS). The governments of these countries regularly gather the sector representatives to provide updates on resolutions and potential changes that could impact the fishery [19].

The fisheries sector participates in the MEDAC [11]. MEDAC is comprised of European and national organizations representing the entire fishing sector and other stakeholders (e.g., environmental organizations, consumer organizations, sport/recreational fishing associations) operating under the CFP in the Mediterranean region. MEDAC's mandate includes providing advice on fisheries management and socio-economic aspects to support the Mediterranean fisheries sector. In general, these perspectives are shared with Member States and European institutions to support the realization of the CFP's objectives [12,19].

1.4. Historical, Social, and Political Context

In order to gain a comprehensive understanding of the fishery management and product safety challenges within a complex environment, it is imperative to consider the historical, social, and political context in which these issues arise [23]. Firstly, akin to the current situation in several coastal Mediterranean countries like North Africa and Turkey, the recent political landscape in the Balkan regions has been turbulent, diverting attention away from the management of fisheries towards more urgent matters [12].

Furthermore, like other parts of the Mediterranean, Croatia acceded to the European Community recently. Previous relations between these two main actors in the Adriatic, Croatia and Italy, were, therefore, plagued by a lack of easy agreement to make this policy possible, according to Carpi et al. [12]. This situation is further exacerbated by the fact that fishers still play an important role in political decisions. Furthermore, the Italian situation is characterized by a history of indiscriminate license allocation, a weak data collection system until the early 2000s, and a general lack of political interest in the issue (often reflected in a lack of control and conflict). Generally, it is even more complicated due to the conflicts between fishers (northern vs. southern, Italian vs. Croatian, and even between categories). This situation undermined the possibility of a joint agreement or full cooperation [12].

Italy and Croatia are the primary nations responsible for the majority of catches in the Adriatic Sea [24]. Italy focuses its efforts on catching anchovy, while Croatia primarily targets sardines. These two species are harvested throughout the year by pelagic trawlers and purse seiners, with a particular emphasis on the Northern region of the basin [12]. The Croatian fishing industry went through a phase of forced closure in the 1990s due to the wars in the former Yugoslavia. After the end of the war, the fleet was updated with the introduction of large purse seiners, which now form a major part of the fleet in the fishing industry [24]. Regarding the other biggest fishery producer in the Adriatic basin, Italy, its share of anchovies and sardines accounts for 30% of the total national catch [10,11]. In Croatia, small pelagic fish account for approximately 80% of the total national catch [15].

Anchovy landings have fluctuated cyclically over the years, reaching very high levels in the late 1970s and early 1980s, partly due to the availability of European Community subsidies, and again in the late 2000s [25]. Generally, the number of landings has increased, while both peaks were followed by more or less significant declines [12]. Meanwhile, the number of sardines landed has plummeted from around 90,000 tons in the early 1980s, reaching a historic low of 1900 tons in 2005. Landings subsequently increased again, with a sharp increase in 2007. This is mainly due to a significant increase in Croatian fishing, with landings reaching 82,000 tons in 2014, the second-highest value in the entire series [12,26]. The rise and subsequent fall of sardine populations prior to 2000 can be attributed to variations in the advection of Levantine Intermediate Waters (LIW) caused by climatic fluctuations [12].

Following both events, the competent authorities displayed a lack of initiative in implementing measures to facilitate the recovery of the stock or mitigate potential losses in fishing opportunities in hypothetical future scenarios of impaired recruitment. The repercussions of this indifference are now evident: the Italian sector, which has traditionally centered its fishery activities around anchovy, is currently experiencing a decline in the number of vessels and a prevailing sense of dismay [12,24]. Conversely, the Croatian fleet, primarily targeting sardines for tuna farms, remains relatively stable [12]. Nevertheless, the practice of utilizing low-value whole feed-fish species, such as locally caught sardines, for the growth and fattening of tuna in Croatian waters is unlikely to be sustainable in the long run [24]. This is due to the fact that the food conversion ratio, at best, stands at 12.5:1, posing significant challenges to its long-term viability [27,28].

The European Union (EU) has recently directed significant attention and resources towards the fisheries sector due to the abundance of available data, the economic value of these resources, and the shared nature of the fisheries [25]. Carpi et al. [12] argue that this focus has yielded positive outcomes. However, it is important to note that the EU's efforts in this regard have not always been effectively directed. To enhance the effectiveness of these initiatives, it is crucial to ensure the continuous involvement of relevant stakeholders and foster ongoing collaboration with the associated organizations.

2. Fishery Product Consumption and Potential Hazards

2.1. General Considerations

Fish are renowned for being an exceptionally abundant reservoir of essential nutrients that greatly contribute to the overall well-being of the human body (Figure 2).

Figure 2. The advantages and possible risks associated with the consumption of seafood.

Omega-3 fatty acids found in fish have been shown to reduce the risk of cardiovascular disease by lowering blood triglycerides, improving blood vessel function, and reducing inflammation [29]. Also, they are essential for brain development in infants and children and may help maintain cognitive function in adults [30]. Also, omega-3 fatty acids in fish are beneficial for eye health and may help reduce the risk of age-related macular degeneration and other eye conditions [31]. Fish provides high-quality protein, essential for muscle growth, repair, and overall body function [32]. Fish is a nutrient-dense food, containing vitamins and minerals such as vitamin D, vitamin B12, selenium, and iodine, which are important for overall health [33,34]. The regular consumption of fish has been linked to a lower probability of developing depression and may have mood-enhancing effects [35].

As a result of the growing levels of contaminants linked to human activities such as industrial operations, mining activities, agricultural practices, and the generation of household waste, there has been a noticeable increase in environmental contamination worldwide [36] (Figure 2). Aquatic organisms, such as fish, have the ability to accumulate pollutants both through direct exposure to contaminated water and indirectly through the food chain, while the bio-concentration of potentially harmful substances, mainly represented by heavy metals, pesticides, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) in aquatic organisms present a major threat to human health. Given their prominent position at the highest level of the aquatic food chain, fish serve as a valuable bio-indicator for evaluating the overall health and condition of aquatic ecosystems [37].

2.2. Heavy Metal Pollution in the Adriatic Sea

Heavy metals have been used by humans for many different activities for thousands of years. Despite the fact that the adverse effects of these elements are largely understood, their exposure remains prevalent, particularly in developing countries. The Mediterranean Basin is a semi-occlusive ocean and is characterized by low water circulation. It is all these factors add both anthropogenic and natural metals to the basin, making the Mediterranean Sea one of the most polluted waters in the world [38]. Furthermore, the Mediterranean basin is commonly recognized as a hotspot for the contamination of sediments, water, and biota by several elements, including heavy metals and organic pollutants [38,39]. In the forthcoming decade, it is imperative to examine whether the Adriatic Sea, as an integral component of the Mediterranean basin, will witness any changes in the state of pollution in its waters caused by heavy metals, PCBs, and PAHs. This review will solely concentrate on the presence of these elements in biota, disregarding their presence in sediment or water. This approach is directly relevant to the assessment of human consumption of these products.

At first sight, the Adriatic Sea is inevitably impacted by pollution in its marine and coastal ecosystems due to human activities, including resource exploitation, agricultural practices leading to land runoff, urban development along the coast, and various maritime transport activities such as harbor operations and ballast water management. Heavy metal pollution in the Adriatic region can be traced back to sources like oil refinery plants [40], metallurgic industries like the Taranto industrial plants [41], land mining activities, such as the mercury mine in Idrija, Slovenia [42], municipal-sewage outflows [43], oil and gas extraction plants [44]. This pollution is of particular concern due to the high concentration of heavy metals in biota, which are a significant food source for humans.

Contamination of bivalve shellfish, such as mussels, clams, and oysters, through filtration, is a significant fact due to their filter-feeding behavior, which makes them vulnerable to accumulating various contaminants present in the water.

The examination of heavy metals led to the discovery that the contamination level of bivalve mollusks across the Adriatic Sea's coastlines remained below the European Union's established standards. Nevertheless, it is important to acknowledge that for some exceptions, Chromium (Cr), Lead (Pb), Cadmium (Cd), and total mercury (Hg) slightly exceeded the permissible limits [45,46]. The evaluation of the risk linked to the utilization of mollusks for human health indicated that there is no apparent risk for individuals who consume these mussels moderately. From these studies' results, it is crucial to regularly and carefully monitor the concentrations of heavy metals in order to ensure the safety of consumers' health [45]. However, it is important to note that there may still be a potential risk for vulnerable groups, like women of childbearing age and children, as well as for individuals who regularly consume shellfish or consume them at high levels. This potential risk is particularly relevant for those who frequently consume species like murex, where Cd concentrations higher than 1 mg kg^{-1} were commonly observed in the north-western Adriatic, according to Bille et al. [46]. Bogdanović et al. introduced a proposal that has the potential to assist individuals who frequently ingest significant quantities of shellfish, with the aim of harmonizing their exposure levels with the acceptable risk threshold. This recommendation is based on a study conducted in 19 locations along the eastern Adriatic Coast in Croatia. Despite the results indicating that the levels of pollutants in the shellfish samples examined mostly complied with the regulations set by the European Union, it is essential to mention that three samples exceeded the upper limits for Pb, Cd, and total Hg concentrations. [47]. In a previous study, Tanaskovski et al. noted that the risk assessment of these elements through mussel consumption indicated that weekly intake of 250 g of mussels over a human lifetime is unlikely to have adverse health effects, considering the element concentrations in *M. galloprovincialis* from the Boka Kotorska Bay, except for Zr concentration. According to the medical literature, high levels of Zr were detected in farmed mussels harvested from the same Bay suggest that consuming more than 140 g per week could pose health risks over a human lifetime [48].

The levels of Pb, Cd, and total Hg in two species of squids, *Loligo vulgaris* and *Todarodes sagittatus*, from the northern Adriatic Sea in Italy were analyzed [49]. The results indicated that flying squids displayed Hg concentrations that were three times greater and Cd concentrations that were one hundred times greater than those observed in European squids. This disparity was significant to the extent that more than 6% and 25% of the samples exceeded the maximum limits for Hg and Cd, respectively, as established by the current legislation [49].

The contamination with heavy metals is also present in many fish species in the Adriatic subbasin. Thus, in a separate investigation on the two most cultivated fish species in the Adriatic, *Dicentrarchus labrax* and *Sparus aurata*, analyzing the majority of metal concentrations in commercial fish did not pose any issues for human consumption [50].

Again, a separate study from the Albanian Adriatic coast assessed the bioaccumulation levels of various heavy metals in fish sourced from the Ishmi river discharge into the Adriatic Sea, Albania. Heavy metal concentrations (Hg, Pb, Cd) were analyzed in the muscle tissues of approximately thirty different fish species. The heavy metal concentrations detected in the fish muscles in this study complied with the international regulatory limits, indicating that they are safe for human consumption [51].

An Italian study conducted by Di Lena and colleagues emphasized the presence of total Hg levels among many fish species, both marine and freshwater species, originating from both intensive and extensive aquaculture systems, including crustaceans captured along the Central Adriatic and Tyrrhenian coasts of Italy. The specimens of large-size pelagic and demersal species occupying high trophic levels were found to exceed the limits set by the European Commission. These authors suggest the importance of diversifying seafood consumption and making informed choices, including crustaceans, by opting for less Hg-accumulating species [52].

In the South Adriatic Sea near Montenegro involved the examination of metals (Pb, Cd, Cu, Fe, Mn, Ni, Cr, Zn) and radionuclides (137Cs, 40K, 214Bi, 228Ac). Six fish species were used to analyze the levels of metals three mullet species along with *Merluccius merluccius*, *Dicentrarchus labrax*, and *Sparus aurata*. None of the muscles exceeded the limits set by EU regulations for toxic trace elements Pb and Cd [53].

In Croatia, a study of white and blue sea fish was conducted to determine if the recorded levels of heavy metals analyzed could pose a threat to consumer health. The analysis revealed that the levels of heavy metals, such as Pb and Cd, in both groups were below the legal limits set by the European Union. For a few samples, Hg levels exceeded the permissible threshold, and also it was noted that arsenic (As) was present in almost all samples. Considering the dietary patterns and frequent consumption of fish in Croatia, it can be concluded that there is no significant risk of adverse health effects [54].

Another study investigated the concentrations of total Hg and mineral element Se in the muscle tissue of 12 commercially significant fish species obtained from 48 sites located in the eastern Adriatic Sea. The findings suggest that consuming two meals a week consisting of small pelagic–neritic and bento-pelagic fish can serve as a valuable source of essential Se without posing a risk of toxic Hg exposure for children and women during their vulnerable reproductive period [55].

The levels of Hg, Cd, Pb, and As through the ingestion of *Umbrina cirrosa* and *Sciaena umbra* fish species were analyzed among the high-level fish consumers. In general, the detected levels generally fall below the maximum permissible limits for human consumption, except for Cd. Non-carcinogenic risks were generally not a cause for concern, except for Hg. From this study, it is strongly advised to conduct regular monitoring of metal (loid) levels in these fish due to the identified health risks, particularly among high-level fish consumers, stemming from the presence of Hg and Cd [56].

The levels of heavy metal Hg were analyzed based on the analysis of sediments, water, and organisms in the Marano and Grado Lagoon in the northern Adriatic Sea, Italy. From this study, the biota sediment accumulation factor (BSAF) values indicate a low bioavailability of Hg for transfer from sediment to biota. Furthermore, the Target Hazard

Quotient (THQ) calculated suggests that there are no immediate concerns regarding adverse effects on human health, at least in the Marano basin [57].

2.3. Contamination of Biota with Persistent Organic Pollutants

Contamination of biota with persistent organic pollutants (POPs) is a significant environmental concern due to their persistence, bioaccumulation, and potential adverse effects on ecosystems and human health. POPs are organic compounds that resist degradation, persist in the environment, bioaccumulate through the food web, and pose risks to human health and the environment. Some examples of POPs include polychlorinated biphenyls (PCBs), Organochlorine pesticides (OCPs), Polybrominated diphenyl ethers (PBDEs), Hexachlorobenzene (HCB), Dioxins, Perfluorinated compounds (PFCs) [58].

In one research work conducted at a tuna farm located in the Croatian Adriatic, the concentrations of PCBs and OCPs in different tissues of farmed Bluefin tuna (*Thunnus thynnus*) were analyzed. Based on the results, it can be concluded that the farmed tuna from the Adriatic Sea exhibited moderate contamination with persistent organic pollutants (POPs), primarily PCBs. However, the levels detected were below the legal limits and do not pose a risk to humans who consume tuna meat in moderate amounts [59]. In another research, six PCBs and twenty-three OCPs were discovered in anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) samples collected in the Herceg Novi Bay area of the Adriatic Sea. The levels of OCPs in all samples were found to be relatively low, indicating no immediate negative effects. However, it is important to note that potential adverse effects may become apparent as these pollutants accumulate at higher trophic levels. Among the PCBs detected, congeners 153, 138, 180, and 101 were the most prevalent, indicating a higher level of toxicity [60].

In a study in European hake, the levels of six marker PCBs, congeners, and four trace elements in European hake specimens obtained from the Mediterranean Sea were ascertained. The findings indicated that the levels of contaminants in all samples were below the recommended international limits. However, it is worth noting that samples from the Ligurian and Adriatic Sea exhibited higher concentrations of PCBs. The results revealed that the total health risk index (HRI) value was low (<1) in cases of chronic consumption despite the presence of notable Hg concentrations [61].

In a separate investigation carried out by Milićević et al., a total of 24 POPs were analyzed in six pelagic fish species, along with 16 elements and 14 fatty acids. These species are commonly included in the human diet. Among them, sardines exhibited the highest overall fat content, indicating a greater propensity for accumulating POPs and carcinogenic elements compared to the other species. Consequently, this finding suggests that sardines may be considered less safe for consumption [62].

2.4. Contamination of Biota with Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are a significant class of pollutants that contaminate aquatic environments. These compounds are known for their persistence and ability to cause harm to cells, induce mutations, birth defects, and even cancer in both humans and wildlife. The Northern Adriatic Sea, in particular, can be considered a PAH-sensitive marine area due to the heavy shipping traffic and the substantial inputs from Italian rivers that pass through the highly industrialized areas of Europe [63]. Fish in marine environments can be exposed to PAHs through various sources, such as atmospheric pollution, industrial and domestic sewage, and oil spills. The primary sources of PAHs in the environment are anthropogenic, arising from the incomplete combustion of fossil fuels, wood, oil spills, and ship discharges. It is important to note that PAHs can exhibit different physicochemical properties and characteristic patterns, which can influence their toxicity, uptake, distribution, metabolism, and elimination in organisms [64].

Frapiccini et al. [65] conducted various studies to evaluate the concentration of PAHs in different fish species. Thus, a study investigated the relationship between PAH concentrations and mRNA expression profiles of antioxidant genes (CAT, GST, and SOD) in the muscle of sexually inactive female red mullet (*Mullus barbatus*) during different seasons. The downregulation of certain oxidative stress biomarkers during the winter season suggests that red mullets may be more susceptible to the effects of PAHs during this winter season [65]. In another study, the same authors analyzed 16 PAHs, which have been designated as priority pollutants by both the EU and the United States Environmental Protection Agency (US EPA) due to their carcinogenic and mutagenic properties. The research delves into the levels and distribution of PAHs in various tissues of two fish species (*Solea solea* and *Mullus barbatus*) from a significant fishing area in the Northern and Central Adriatic Sea. This PhD thesis offers fresh insights into the primary biological, chemical, and environmental factors influencing PAH levels in fish tissues, including those that are edible. Additionally, it explores the correlation between PAH levels and the mRNA expression levels of certain antioxidant enzymes, along with lipid peroxidation, providing novel and valuable information on the biological responses of wild Adriatic fish exposed to PAH pollution [66]. Another study of the same collaborators involved the examination of edible fillets from 380 specimens of *Mullus barbatus* to determine the levels of individual PAHs, total PAHs, as well as low-, medium-, and high-molecular-weight (MW) PAHs. The results indicate the presence of a significant detoxification mechanism, primarily affecting the heavier PAHs, during the spawning and post-spawning phases. The reproductive stage and seasonality were identified as key factors influencing the accumulation of heavier PAHs, while total lipid content and age had a limited impact, and body size showed no effect at all [67]. The last investigation of Frapiccini et al., represents the study conducted on *S. solea* in the Adriatic Sea, shedding light on the potential correlation between microplastics (MPs) and PAHs. The initial findings indicate that MPs do not serve as carriers for PAHs. Moreover, the primary source of PAH contamination in fish originates from the surrounding environment, specifically marine sediments where the sole species resides. These conclusions are substantiated by the strong association observed between PAH concentration in marine sediments and fish, the absence of a relationship between PAH fish concentration and MPs, and the varying PAH concentration across the three different fish tissues examined. Additional field studies have already been planned to further enhance our comprehension of the interplay between MPs and PAHs in marine ecosystems [68].

2.5. Antibiotic Resistance in Fish Farming

The use of antibiotics in fish farming is primarily aimed at preventing and treating bacterial infections that can spread rapidly in crowded fish populations. However, the overuse and misuse of antibiotics in this industry have contributed to the development and spread of antibiotic-resistant bacteria. These bacteria can then be transmitted to humans through the consumption of contaminated fish or through environmental contamination [69].

The emergence of antibiotic-resistant bacteria (ARB) and the rise of multi-drug-resistant bacteria (MDR) are direct consequences of the selective pressure imposed by antibiotics. These MDR bacteria have become increasingly challenging to control and eliminate. However, in the salmonid farming industry in Europe and America, the development of effective vaccines has proven beneficial. These vaccines have significantly reduced the need for antimicrobial agents in combating bacterial diseases [70]. Notably, antibiotic resistance has been frequently observed against Tetracyclines, Fluoroquinolones, sulfonamides, Penicillins, and Macrolides [71,72].

The Vibrio species exhibit a broad geographical distribution and possess the capability to cause disease in aquatic organisms. In order to investigate this further, a comprehensive study was undertaken wherein gill and skin swabs were obtained from 110 European seabass that were being farmed. The objective was to determine the presence of Vibrio in these samples. The research team successfully isolated *Vibrio* spp. from a range of environmental samples that were collected over a span of three years from a fish farm situated in the Adriatic Sea, specifically in Croatia. The analysis indicated that *V. alginolyticus* was the most prevalent species in European seabass, followed by *V. anguillarum*. Upon analysis, these two isolates were found to differ genetically and in terms of antibiotic resistance. The results of the study confirm the seasonal nature of vibriosis incidence and the presence of pathogenic *V. anguillarum*, which heightens the risk of vibriosis [73]. Also, the cultivable microbiota linked to plastic debris gathered by commercial fishing trawlers in the southeastern Adriatic Sea was the object of a study conducted by Kapetanović et al. [74]. The prevalence of Vibrio was notably higher on plastic debris compared to the adjacent seawater and sediment. All identified *Vibrio* strains exhibited resistance to ampicillin and vancomycin, with resistance to other antibiotics varying depending on the specific species [74].

Another research presents compelling evidence that the exclusive reliance on primary treatments in urban wastewater management leads to significant contamination of marine coastal waters with microbial pollutants. Conversely, conventional treatments fail to completely eradicate antibiotic resistance genes (ARGs) in treated wastewater. By incorporating molecular techniques, the assessment of depuration efficiency can be enhanced, paving the way for innovative approaches in urban wastewater treatment [75].

Also, the presence of antimicrobial resistance genes can be observed in the aquatic environment. In this particular investigation, a combination of phenotypical, biochemical, and molecular techniques was employed to examine a group of marine strains that were isolated from aquaculture farms in Italy. By comparing the phylogeny of enzymes and the clustering of strains based on sampling locations and dates, it was determined that certain clones of Multi-Drug Resistant (MDR) *Shewanella* algae have spread along the Italian Adriatic coast [76].

Pavlinec et al. recently conducted a study on *Vibrio harveyi*, a major cause of vibriosis in fish aquaculture. The objective of this study was to provide a comprehensive description of the biochemical, physiological, and genetic characteristics of three serologically distinct strains of *V. harveyi* that were isolated from farmed European Sea bass in the Adriatic Sea. The analysis revealed a significant number of nonsynonymous variations among the sequences of the three strains. Furthermore, six virulence genes, which were previously not associated with vibrio virulence, were detected in all three strains under investigation [77]. The Vibrio frequency was detected using the AqADAPT dataset, which aids in the creation of management and adaptation tools through the provision of microbial parameters of seawater and biochemical analysis of culturable bacteria in two sites adjacent to floating cage fish farms in the Adriatic Sea. This dataset encompasses the assessment of various physicochemical parameters of seawater and serves as a valuable resource for monitoring water quality at varying depths surrounding aquaculture operations [78].

The digestive gland of Mediterranean mussel (*Mytilus galloprovincialis*) has been identified as a key component in the detoxification of various emerging pollutants, including antibiotics, herbicides, and insecticides. Palladino et al. conducted a study that highlighted the ability of this sentinel species to naturally resist exposure to xenobiotics of both natural and anthropogenic origins. The findings suggest that the microbiome associated with the digestive gland of *M. galloprovincialis* plays a crucial role in the detoxification process, especially in environments with high levels of anthropogenic pressure. This underscores the potential of mussel systems as effective tools for bioremediation efforts [79]. Another research work, using bivalve mollusks intended for human consumption as a sample, was conducted to investigate the occurrence and susceptibility of potentially harmful bacteria, such as *Salmonella* spp. and *Vibrio* spp. The findings revealed that one strain of *S. typhimurium* exhibited multidrug resistance (MDR) to sulfamethoxazole, trimethoprim, tetracycline, gentamicin, and ampicillin. Additionally, 41.3% of the *Vibrio* strains displayed MDR, primarily against sulfonamides, penicillin, and cephem. However, all the tested *Vibrio* isolates demonstrated susceptibility to azithromycin, chloramphenicol, tetracycline, amoxicillin/clavulanic acid, gentamicin, streptomycin, amikacin, and levofloxacin [80].

This research study presents novel findings regarding the culturable skin bacteria associated with healthy European seabass in both antibiotic-treated and antibiotic-free culture conditions. Notably, certain pathogenic microbiota known to affect fish health were identified, including *V. alginolyticus*, *V. anguillarum*, and *V. harveyi*. It is worth mentioning that the Vibrio strains exhibited a higher level of resistance to specific antibiotics when compared to previous studies conducted in similar contexts [81].

2.6. Harmful Algal Blooms in the Adriatic

Harmful algal blooms (HABs) are observed globally and have severe effects on fisheries, aquaculture, and tourism [82–84].

The Adriatic Sea, like numerous other marine environments, is vulnerable to harmful algal blooms (HABs) triggered by various species of algae that generate toxins or detrimental effects on marine ecosystems. Several harmful algae commonly observed in the Adriatic Sea encompass dinoflagellates, diatoms, and cyanobacteria [85].

Dinoflagellates, a varied collection of unicellular algae, encompass numerous species with the ability to create detrimental algal blooms. Certain dinoflagellates, including *Alexandrium* spp., *Gymnodinium* spp., and *Karenia* spp., possess the capability to generate toxins that result in paralytic shellfish poisoning (PSP), diarrheal shellfish poisoning (DSP) and various health complications in both humans and marine organisms [85,86].

Diatoms, a different category of algae found in the Adriatic Sea, have the ability to produce harmful blooms in specific circumstances. Certain diatoms, like *Pseudo-nitzschia* spp., are capable of generating domoic acid (DA), a neurotoxin that can lead to Amnesic Shellfish Poisoning (ASP) in humans and other animals [87].

While not classified as true algae, cyanobacteria, commonly referred to as blue-green algae, can also create harmful blooms within the Adriatic Sea. Various cyanobacteria species, such as *Microcystis* spp. and *Anabaena* spp., have the capacity to produce toxins like microcystins and anatoxins, which present risks to human health and aquatic ecosystems [88].

Main Marine Biotoxins Found in the Adriatic Subbasin

In the Adriatic subbasin, certain marine biotoxins are a cause for concern due to their potential to induce negative effects on human health through the consumption of contaminated seafood. Among the most significant marine biotoxins in the Adriatic area are the following:

Paralytic shellfish toxins (PSTs) are a category of potent neurotoxins generated by various marine dinoflagellates, including *Alexandrium* spp., *Gymnodinium* spp., and *Pyrodinium* spp. These toxins have the potential to amass in filter-feeding shellfish like mussels, clams, oysters, and scallops, thereby presenting a notable threat to human health upon ingestion. PST can cause a range of symptoms in humans, including tingling or numbness of the lips and extremities, dizziness, nausea, vomiting, and, in severe cases, respiratory paralysis and death. It is essential to monitor shellfish harvesting areas for the presence of these toxins and to adhere to regulatory guidelines to prevent paralytic shellfish poisoning [86,89].

Saxitoxin (STX) is among the distinct paralytic shellfish toxins and is recognized as the most extensively researched and well-known toxin of the group of PSTs. Saxitoxin functions by inducing paralysis and respiratory blockage when consumed in elevated quantities [89–95].

Ujevic and colleagues conducted an analysis on the levels of STX in shellfish species such as rough cockle *Acanthocardia tuberculata* and smooth clam *Callista chione*. The results of the study indicated that both shellfish species examined had concentrations of these biotoxins that fell below the regulatory thresholds established by the European Commission [90].

Talic et al. found that the levels of STX detected in *M. galloprovincialis* were not considered to pose a significant risk to consumers. However, the authors recommended implementing a regular monitoring program [89]. On the other hand, Ragni et al. reported the presence of *Alexandrium minutum* and *Gymnodinium catenatum* algae in the northwestern regions of the Adriatic Sea (Italy). These algae were identified as potential producers of SXT, indicating their detrimental presence in areas designated for mollusk cultivation [91].

In a comprehensive investigation spanning 14 years (2006–2019), Accoroni et al. conducted a study to examine toxicity events along the Italian coasts and establish a correlation with the distribution of potentially harmful species. The study revealed that among the toxins identified, Saxitoxin (STX), Okadaic Acid (OA), and Dinophysistoxin A (DA) were the most commonly reported. It is worth noting that instances of seafood toxicity, when identified, have generally remained within acceptable safety thresholds [96].

Gonyautoxins (GTXs) are a group of structurally related toxins that can cause paralytic shellfish poisoning. Nevertheless, in the case of Adriatic mollusks, where the biotoxin was identified, the concentrations were not at levels that posed a threat to consumers when consuming them [90,93]. The amnesic shellfish toxin (AST)_ is synthesized by specific diatom species, notably *Pseudo-nitzschia* spp., and is known to build up in shellfish like mussels, leading to the development of ASP in individuals. ASP is characterized by manifestations such as temporary memory impairment, disorientation, convulsions, and, in critical instances, unconsciousness and fatality [97]. The main amnesic shellfish toxin are the followings:

DA serves as the primary toxin linked to ASP. This neurotoxic amino acid has the ability to accumulate in filter-feeding shellfish, namely mussels, clams, oysters, and scallops, particularly during harmful algal blooms dominated by *Pseudo-nitzschia* species. Exposure to DA can result in a range of symptoms in humans. These include gastrointestinal issues like nausea, vomiting, and diarrhea, as well as neurological symptoms such as headaches, dizziness, confusion, short-term memory loss, seizures, and, in severe cases, coma and even death [90,98–101]. DA was identified in minute quantities in three species under investigation—European oysters (*O. edulis*), Queen scallops (*A. opercularis*), and ascidians of the *Microcosmus* spp., which were gathered from the eastern coast of the Northern Adriatic Sea over the course of the year. Queen scallops tended to accumulate DA more frequently and at higher levels. The peak concentrations of DA were observed during the colder months [98]. Arapov et al. conducted a study in the Velebit Channel (central Adriatic Sea), where cultures of *Pseudo-nitzschia* were established from seawater samples in 2019. The presence of DA was confirmed in all isolates that were examined. The cellular DA content ranged from 0.0022 to 0.0855 pg cell^{-1}. The highest levels of cellular DA were detected in the early stages of the cultures [99]. In a subsequent study by Ujevic et al., DA concentrations were measured in natural populations of the warty venus, Venus verrucose, situated in the semi-enclosed Kaštela Bay in the middle of the Adriatic Sea. DA was only found in 5.4% of the samples, with concentrations ranging from 0.16 to 13.30 mg DA eq./kg [101].

Diarrhetic shellfish toxins (DSTs) are synthesized by specific marine dinoflagellate species, namely *Dinophysis* spp. and *Prorocentrum* spp. These toxins have the ability to accumulate within shellfish, particularly mussels, leading to the occurrence of DSP in humans. DSP is characterized by a range of symptoms, including diarrhea, nausea, vomiting, abdominal pain, and chills, which are commonly observed in affected individuals [86,102]. The main DSTs detected in the Adriatic include: Okadaic Acid (OA) and Dinophysistoxins (DTXs).

Okadaic Acid is one of the most well-known diarrhetic shellfish toxins. It is a polyether compound that inhibits protein phosphatases, leading to gastrointestinal symptoms such as diarrhea, nausea, vomiting, and abdominal pain when consumed by humans [102]. Rubini et al. conducted a study in the Northwestern Adriatic Sea (Italy) to investigate the presence of OA in bivalve mollusks. Out of the 706 samples tested, 246 were found to be positive for OA. Among these positive samples, 30 exceeded the legal limit. The authors emphasize the urgent need to establish an "early warning" system that can effectively monitor the production areas of live bivalve mollusks. Such a system would enable optimal management of the affected plants in critical situations [102]. In a separate study, Capoccioni et al. examined cultured bivalve *M. galloprovincialis* for the presence of OA. The positive samples showed OA levels reaching 139 $\mu g \cdot kg^{-1}$, which is below the permitted limit of 160 $\mu g \cdot kg^{-1}$ [103]. Furthermore, a subsequent study analyzed the levels of OA in *M. galloprovincialis* along the coasts of the Central Adriatic Sea from 2020 to 2021. Among the samples that tested positive, only 22% exceeded the maximum permitted limit of 160 $\mu g \cdot kg^{-1}$, with a mere 3.3% surpassing this threshold [104].

Dinophysistoxins are a group of closely related toxins produced by *Dinophysis* spp. They are structurally similar to Okadaic Acid and can cause similar gastrointestinal symptoms. Based on the bibliographic investigation, the presence of DTX was observed in the study conducted by Rubini et al. in the Northwestern Adriatic Sea (Italy). The levels that exceeded the legal limits were found in just 4.24% of the samples that were analyzed [102].

3. Effects of Climate Change on Fishery Products

The distribution of plants and animals on Earth is greatly influenced by the climate, which is considered one of the key abiotic factors [1]. This influence is exerted through a combination of direct and indirect effects. In the case of poikilothermic organisms like fishes, whose body temperature varies with the environmental temperature, the temperature plays a crucial role in shaping their survival, reproduction, and resource utilization patterns. Consequently, these individual-level impacts can have significant implications for population and community structures [105]. Additionally, indirect effects can also come into play, such as alterations in water circulation, which can, in turn, affect larval dispersal and recruitment processes [106].

Fish have been utilized as indicators of environmental changes for an extensive period [107,108]. Their remarkable ability to disperse, ecological differentiation, sensitivity to temperature, and ease of identification render them exceptional indicators of the consequences of climate change. Moreover, the detrimental effects of climate change on the biology, fertility, growth, and biodiversity of aquatic, terrestrial, and aerial animals have been widely acknowledged [109]. Additionally, Pörtner and Peck assert that the influence of climate change on individual organisms is apparent throughout their entire life cycle, thereby impacting species populations, communities, and the overall functioning of the ecosystem [1,110].

Local atmospheric conditions play a crucial role in shaping the hydrological characteristics of the Adriatic Sea. For example, a study carried out by Ferrarese et al. [111] highlighted the sudden alterations in circulation and temperature patterns of the Adriatic Sea in response to intense winds. It is worth noting that the North Adriatic area exhibits the greatest seasonal variation in sea surface temperature (SST) among all regions in the Mediterranean [112]. Furthermore, the potential disruption of thermohaline circulation in the Adriatic Sea as a result of climate change could have significant implications for deep-sea pelagic and benthic organisms, particularly impacting biodiversity in areas like the Jabuka Pit [113]. Numerous publications in recent years have also recognized the influence of climate change on hydrological and biological processes in the Adriatic Sea [114–116].

Climate warming can elicit diverse reactions from different species. One potential response involves taxa migrating towards cooler habitats, such as shifting towards the poles and higher latitudes. This can lead to elevated rates of global extinction and the reorganization of local communities due to local extinctions and the expansion of species that can tolerate higher temperatures [117]. A study focused on the mobile fauna, particularly fishes, in the Adriatic Sea, has identified several theoretical outcomes that may arise [1]. These outcomes encompass the expansion of species distributions towards the northern limit, primarily affecting thermotolerant species through northward expansion. Furthermore, there could be a decrease in the distribution of species that prefer cold water, resulting in a northward shift in the center of population distribution. Consequently, other species may seek refuge in the northern regions of the Adriatic Sea [1]. In addition to the phenomenon of population redistribution, which typically occurs in a northward direction among native Mediterranean species, known as "meridionalization", the introduction of alien species from tropical regions, referred to as "tropicalization", also exerts a significant influence on the composition of faunal communities in the Mediterranean and Adriatic Sea [118].

Many reports of northward migration have been documented in the Adriatic Sea, with even young individuals of certain thermotolerant fish species that were once rare or absent now being observed. The presence or increase in numbers of particular thermotolerant species in the Adriatic Sea is often attributed to rising water temperatures, although differentiating this factor from other possible explanations poses a significant challenge [119,120].

It is highly likely that the majority of potential factors are closely connected to the rising average sea temperatures. In the last 25 years, a significant number of thermotolerant fish species have been recorded in the Adriatic Sea for the first time, with their presence possibly linked to climate change [121,122]. The effects of climate change are also responsible for aiding the migration of *Lessepsian* fish species. The success of non-commercial species is boosted by intense fishing, which decreases competition from commercial species for the same resources. Consequently, this allows previously uncommon species to flourish and establish larger and more resilient populations [116]. Furthermore, it is important to note that the Adriatic Sea is not an isolated ecosystem, and changes in other regions have substantial implications for its overall ecological balance [115,116]. This is particularly significant concerning the presence of *Lessepsian* fish species, as their migration into the Adriatic is influenced not only by climate change but also by the existence of established populations in southern areas. These established populations likely act as recruitment areas for the subsequent northward expansion of *Lessepsian* fish species [122]. The occurrence of *Lessepsian* species in the Adriatic Sea is probably facilitated, if not a consequence, by periodic influxes of water originating from the eastern Mediterranean Sea (BiOS) [1].

In addition to the introduction and spread of non-native species, there are also notable changes affecting the populations of native fish species. These changes are evident in various ways, such as increased numbers, expansion towards northern regions, or a decrease in the presence of certain species. It is highly likely that the warming of water will have negative impacts on cold water species, while species that can tolerate higher temperatures will benefit from it. This issue is of great importance for the Adriatic Sea, as the effects of global warming are particularly severe in partially enclosed seas [123]. There are already signs that certain cold-water fish species, specifically the European sprat (*Sprattus sprattus*) and the cold-water species whiting (*Merlangius merlangus*), have experienced a decline over the past thirty years [124].

The rise in population levels is particularly noteworthy when considering species such as the yellow barracuda (*Sphyraena viridensis*), flying gurnard (*Dactylopterus volitans*), ornate wrasse (*Thallasoma pavo*), grey triggerfish (*Balistes carolinensis*), white trevally (*Pseudocaranx dentex*), Mediterranean parrotfish (*Sparisoma cretense*), and fangtooth moray (*Enchelycore anatine*). These species exhibit potential distributional shifts, making their increased abundances even more intriguing [120].

The Serranidae family, which used to be prevalent in the southern Adriatic Sea, has undergone a migration towards the north. This migration holds particular significance for two species, namely the white grouper (*Epinephelus aeneus*) and the mottled grouper (*Mycteroperca robra*). Initially documented in the southern Adriatic Sea in 1999 and 2000, respectively, these grouper species have expanded their range towards the north and are now occasionally sighted in the southern and central regions of the Adriatic Sea [120,125].

Climate-induced alterations are expected to bring about changes that will affect the services provided by ecosystems, particularly in important sectors such as aquaculture and fisheries [118,126]. The marine fishery industry is particularly vulnerable to the impacts of climate change, which can lead to both positive and negative economic consequences [126,127]. The impact on fishing communities will vary depending on their exposure to climate change, the vulnerability of key species and ecosystems, and the capacity of fishers to adjust to changing conditions [128].

The dynamics of fisheries may be impacted by both the processes of "meridionalization" and "tropicalization" of catch, which describe the increase in warmer-water species compared to colder-water species. This shift in species distribution is anticipated to affect the availability of fish to fisheries. The effects of global warming on landings could lead to changes in the intensity and spatial distribution of fishing efforts, as exemplified by the case of the European Lobster (*Homarus gammarus*) in the eastern Adriatic Sea [129]. The vulnerability of this fishery to climate change is determined by previous alterations in fish stocks, which influence the species composition and abundance in commercial catches [116]. Consequently, it is expected that climate change will have diverse impacts on different sectors of the fishing industry. However, it remains uncertain whether the Mediterranean fleet's diversity in terms of catches and vessels will enhance the adaptive capacity of these regions [130].

The presence and behavior of small pelagic fish are crucial ecological indicators that reflect the overall health of an ecosystem. These fish species are particularly sensitive to climate forcing, which makes them highly vulnerable to the impacts of climate change [131]. This susceptibility poses a significant threat to purse-seine fisheries, which heavily depend on these fish for their operations [115]. Furthermore, fishing activities can result in a decrease in habitat complexity and changes in the structure of the benthic community. These alterations can have profound effects on the abundance and distribution of economically important fish species like hake (*Merluccius merluccius*), mackerel (*Scomber scombrus*), and blue whiting (*Micromesistius poutassou*) [132].

According to Dragičević et al. [1], the superior competitive abilities of alien species in acquiring space, shelter, and food resources may result in the displacement of native species. In specific regions, the displacement of native mullets (*Mullus* sp.) by alien goatfishes (*Upeneus* spp.) [133], salema (*Sarpa salpa*) by spinefoot species (*Siganus* spp.), and/or anchovy (*Engraulis encrasicolus*) by round-eye herring (*Etrumeus golanii*) [134] is currently taking place.

Additionally, the Adriatic Sea harbors economically important species, such as tripletail *Lobotes surinamensis* and spinefoots like *Siganus luridus* and *S. rivulatus*, which have the potential to flourish or have already established populations [1]. It is crucial for the countries bordering the Adriatic Sea to enhance the significance of these species through awareness-raising initiatives. These efforts can play a critical role in educating the public about the nutritional benefits of these species, encouraging the development of innovative processed products, and promoting both fresh and processed options in the market. To reduce the pressure on invasive species populations like spinefoots and cornetfish, it is advisable to encourage commercial fishing targeting these species [135]. In the context of Adriatic basin fisheries, Dragičević et al. [1] suggest that this strategy should not only focus on alien species but also include other thermotolerant species, such as *Pomatomus saltatrix*, *Sphyraena viridensis*, or *Balistes carolinensis*, whose populations are on the rise.

4. Future Prospective and Conclusions

Considering the fact that the Mediterranean Sea is recognized as one of the most polluted seas in the world, an investigation was conducted in the Adriatic Sea subbasin to assess the pollution levels of heavy metals, PCBs, PAHs, and marine biotoxins. The aim was to determine if these pollutants reached levels that could potentially endanger the health of consumers who consume fish caught in this sea. An analysis of bibliographic data from the past five years revealed that the pollution levels of heavy metals in fish did not pose a significant risk. While most studies indicated that the pollution levels in bivalve mollusks were below the permitted thresholds, there were isolated cases where levels of Cr, Pb, Cd, and total Hg slightly exceeded the permissible limits. It is crucial to highlight that there might still be a potential risk for vulnerable groups, such as women of childbearing age, children, and individuals who regularly consume shellfish or consume them in large quantities.

Regarding the contamination of biota with POPs, including OCPs and PCBs, the detected levels were below legal thresholds and did not pose a risk to humans who consume fish in moderate amounts.

In terms of PAH contamination, the Northern Adriatic Sea, in particular, can be identified as a PAH-sensitive marine region due to the heavy maritime traffic and significant inputs from Italian rivers that flow through highly industrialized areas of Europe. Furthermore, the analysis of POP concentrations did not indicate any HI or CR risks for consumers.

In the context of antibiotic resistance in fish farming, recent observations have revealed that Vibrio strains, commonly present in marine waste such as micro- and macro-plastics, demonstrate an increased resistance to specific antibiotics.

The detrimental effects of harmful algae are evident even in the Adriatic Sea. Dinoflagellates, diatoms, and cyanobacteria are frequently present in this body of water, producing biotoxins that pose a threat to consumers. Despite the prevalence of these algae, only a minority of biotoxins were detected at high concentrations, with the majority falling below permissible levels.

Understanding the impact of climate change on fisheries' income is crucial for the development of effective socioeconomic policies and food sustainability measures in adaptation efforts [136]. Lam et al. emphasize the necessity of conducting thorough economic analyses to evaluate the potential consequences of climate change on global marine fisheries [136]. While aquaculture is seen as a viable solution to offset financial losses from fishing and improve food security in the face of climate change, there is a concern that it could lead to a decrease in seafood prices, thereby reducing the earnings of fisheries [1]. In the Adriatic basin, many coastal communities rely on marine resources for their livelihoods and food security [1,120]. These resources are already under significant pressure from overfishing, pollution, coastal development, and habitat degradation, with climate change presenting an additional threat to coastal ecosystems and communities [137]. For instance, the warming of waters is projected to increase Hg methylation, resulting in a 3–5% rise in methylmercury uptake in fish for every 1 °C temperature increase [138]. Environmental contaminants pose a significant risk not only to fish but also to consumer health [139]. Furthermore, the effects of climate change are anticipated to lead to a rise in toxic algae in waters, particularly in marine environments, potentially causing harmful algae blooms. Globally, shellfish poisoning outbreaks are expected to become more frequent due to future climate conditions in the Adriatic Sea and its surrounding lagoons [137,140]. Mol and Coşansu suggest that toxic algae may give rise to paralytic (PSP), Amnesic (APS), diarrhetic (DSP), neurotoxic (NSP), and Azaspiracid (AZP) Shellfish Poisonings, negatively impacting human health as a consequence of global climate change [139].

The increase in temperature and changes in precipitation patterns are projected to enhance the resilience and prevalence of bacteria, viruses, parasites, and fungi. Consequently, there is expected to be a rise in the incidence of foodborne illnesses. Moreover, a slight elevation in water temperature is forecasted to expand the geographical distribution of nematodes and promote their reproduction during the infectious phases across various environments [139]. Particularly in countries within the Adriatic basin, careful attention should be given to the cultivation of rainbow trout and Mediterranean mussels, with a focus on the early detection and prevention of disease outbreaks. Another significant concern arising from climate change is the heightened presence of harmful bacteria in water bodies and aquatic organisms. This is anticipated to have a global impact in the future due to the temperature increases induced by climate change. Shellfish, particularly in the Mediterranean Sea and Adriatic Sea regions, are expected to serve as a primary route for pathogen transmission to humans, given their role as filter feeders and common consumption in raw form [139]. These regions are renowned as top tourist destinations worldwide [126]. Acidification represents another detrimental consequence of climate change on water resources, as crustaceans and mollusks may struggle to develop shells due to reduced calcification. This could ultimately lead to a decline in the availability of these seafood items on our dining tables [138].

To summarize, the impact of climate change on our seafood resources will result in a decline in both the quantity and safety of seafood available. This is primarily due to the adverse effects it brings, including increased pollution levels, the proliferation of parasites and viruses, the rise of infections, acidification, and the presence of toxic substances like shellfish poisoning. In order to mitigate these challenges, it is imperative to establish comprehensive global food safety strategies that aim to reduce greenhouse gas emissions and encourage the adoption of environmentally friendly technologies. Furthermore, it is crucial to develop strategies that specifically address the emerging concerns posed by climate change, as it directly influences the quality and microbiological safety of seafood.

In the future, it will be imperative to assess the susceptibility of natural ecosystems to the introduction of novel species [116] and potential diseases [141] prior to their establishment. Nevertheless, in the Adriatic Sea, similar to the marine environment of the Mediterranean, there has been limited endeavor to improve forecasts regarding the spatial patterns of these species under different climate conditions [142,143]. This information is presently vital not just for the Mediterranean Sea, recognized as one of the most invaded marine areas worldwide [144], but also for the Adriatic Sea, a distinct ecosystem within the Mediterranean that is undergoing a more rapid warming trend compared to the global mean [145].

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