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Review

Impacts of COVID-19 on the Aquatic Environment and Implications on Aquatic Food Production

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Abstract: The COVID-19 pandemic, caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), resulted in ecological changes of aquatic ecosystems, affected the aquatic food supply chain, and disrupted the socio-economy of global populations. Due to reduced human activities during the pandemic, the aquatic environment was reported to improve its water quality, wild fishery stocks, and biodiversity. However, the sudden surge of plastics and biomedical wastes during the COVID-19 pandemic masked the positive impacts and increased the risks of aquatic pollution, especially microplastics, pharmaceuticals, and disinfectants. The transmission of SARS-CoV-2 from wastewater treatment plants to natural water bodies could have serious impacts on the environment and human health, especially in developing countries with poor waste treatment facilities. The presence and persistence of SARS-CoV-2 in human excreta, wastewaters, and sludge and its transmission to aquatic ecosystems could have negative impacts on fisheries and aquaculture industries, which have direct implications on food safety and security. COVID-19 pandemic-related environmental pollution showed a high risk to aquatic food security and human health. This paper reviews the impacts of COVID-19, both positive and negative, and assesses the causes and consequences of anthropogenic activities that can be managed through effective regulation and management of eco-resources for the revival of biodiversity, ecosystem health, and sustainable aquatic food production.

Keywords: COVID-19; aquatic environment; risks; aquatic foods; fisheries; aquaculture

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Citation: Yusoff, F.M.; Abdullah, A.F.; Aris, A.Z.; Umi, W.A.D. Impacts of COVID-19 on the Aquatic Environment and Implications on Aquatic Food Production. *Sustainability* **2021**, *13*, 11281. https://doi.org/10.3390/su132011281

Academic Editor: Samuel Asumadu-Sarkodie

Received: 20 August 2021
Accepted: 3 October 2021
Published: 13 October 2021

1. Introduction

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) caused the coronavirus disease 2019 (COVID-19) that brought severe changes to various facets of human lives world-wide. During the pandemic, which has claimed 4,753,573 lives from 232,029,574 cases in 220 countries and territories by 25 September 2021, essentially all countries have implemented various forms of human movement restrictions to curb the spread. COVID-19 pandemic caused chain ecological changes in both aquatic and terrestrial ecosystems, affected aquatic resources and supplies, altered the livelihood of the littoral communities, and changed the socioeconomics of the global population. Dente and Hashimoto [1] noted that the COVID-19 pandemic has resulted in both positive and negative impacts to the environment and human society. The improvement of water quality and the increase in fish stocks were reported in many countries as many industries and other anthropogenic activities decreased across the globe during the restricted movement period [2–4]. Aquatic ecosystems including lakes, rivers, and coastal waters rapidly responded to the reduced anthropogenic impacts. Braga [5] noted the water transparency in the lagoon of Venice improved during the lockdown to control the spread of the SARS-CoV-2 infection, mainly due to the reduction of urban water traffic and other related human activities. The improvement of water quality and the increase in some aquatic wild stocks in the aquatic environment were reported in water bodies around the world as the results of reduced agricultural, industrial, and commercial activities [6].

However, negative impacts in the sudden surge of plastics, disinfectants, and pharmaceutical wastes due to the fast spread of COVID-19 quickly masked the positive changes seen in the beginning of the pandemic. COVID-19's restriction on human movement resulted in disruptions of various aspects of human lives and altered human behavior. The loss of jobs and income, increased poverty, and disrupted trade and supply chains that could finally cause societal and economic collapses were some of the devastating consequences of the global pandemic. Praveena and Aris [2] reported that the lack of efficient treatment facilities of plastic and medical wastes in Southeast Asian countries resulted in a huge increase of these wastes in water bodies during the lockdown periods. In addition, the COVID-19 pandemic interfered with the supply of basic life necessities, especially water, foods, and sanitation. These negative impacts are more apparent in low-income countries with an inadequate supply of basic necessities, where people would be more vulnerable to the impacts of the pandemic [7]. Thus, the aquatic environment-resource-human nexus during the COVID-19 crisis should be carefully studied to understand the complex relationships and formulate effective strategies to minimize the negative impacts.

2. Impacts of COVID-19 on the Aquatic Environment

The aquatic environment consists of a continuum of aquatic ecosystems from the upstream to the estuary and coastal area, punctuated by creeks and tributaries along the way. Numerous lakes and wetlands in the flood plains and/or river basins also contributed immensely to the lotic-lentic water body complex. With the rapid economic development, especially in developing countries, many of these water bodies are subjected to environmental stressors associated with anthropogenic activities and climate change, resulting in water quality deterioration, harmful algal blooms, loss of productivity, and loss of biodiversity. The appearance of COVID-19 showed both its positive and negative impacts on the aquatic environment (Table 1).

Table 1. Impacts of COVID-19 on the aquatic environment.

Components/ Elements	Impacts/Results	Reasons	References
Water quality	Decrease in total solids, less turbidity	Less human activities and decreased discharges Turbidity levels decreased by 25% due to reduction in human activities	[2,4]
	Improvement in suspended particulate matter	Decreased of SPM by 15.9%	[3]
	Increased water transparency	Reduction in water-based activities due to lockdown	[5]
	Decrease in nutrients	Less agro-based industries, less nutrient rich waters from commercial center and urban areas	[8,9]
	Decrease of some heavy metal concentrations in surface and ground waters	Decrease in industrial discharges	[9]
	Improvement of water quality index (based on DO, BOD, COD, pH and NH_3-N) in rivers and lakes	Significant reduction in industrial and agriculture activities and human encroachment. Closure of industrial and tourism activities	[10]

Table 1. *Cont.*

Components/ Elements	Impacts/Results	Reasons	References
Chlorophyll *a* and Phytoplankton	Decline of chlorophyll *a*	Reduction of nitrogen inflow from the land area	[11]
Bacterial loads	Reduced total coliforms, fecal coliforms, fecal Streptococci, *Escherichia coli*,	Closure of agroindustries: aquaculture, poultry, livestocks	[9]
Resources and biodiversity	Improved; increased deep water shrimp production	Less fishing pressure: reduced anthropogenic activities allowed stock recovery, especially for fast growing species.	[12]
Plastic wastes	Increased personal protection equipment (PPE) and face masks	Higher use in relation to the COVID-19 pandemic	[13–15]
Medical wastes—COVID-19 related pharmaceuticals	Increased chemical contaminants (endocrine disrupting compounds) harmful to aquatic ecosystems and human health.	Higher wastes from hospitals—10 to 20 times higher, less recycling. Environmental concerns on antibiotics and antivirals; ivermectin and azithromycin had high effects in aquatic organisms.	[8,16]
	Impairment of reproductive system in fish	Abnormalities in fish ovaries	[17]
Disinfectants	Strong biocidal properties against bacteria and viruses	Formation of dioxin and other carcinogen in surface waters. High ecological risks	[18,19]
Water as a medium to spread viruses	SARS-CoV-2 detected in feces	Increase of COVID-19 cases and evidence its presence in waste waters	[20–23]
Transmission of virus from wastewater to surface water	Increased virus to surface waters in less treated or untreated sewage	In countries with less efficient waste treatment facilities.	[8,24,25]
Use of WBE (wastewater-based epidemiology)	An efficient, economical, and powerful tool for assessing, monitoring, and managing the COVID-19 pandemic	To prevent contamination of surface and ground water supply for drinking water	[26–28]
Use of technologies	Contain/removal of viral particles	Laser technology	[29]
		Coagulation-flocculation and filtration	[30]
		Natural microbes—Bioremediation technology (virus elimination via predation, antagonism, and nutrient competition)	[31]
		Microagal technology	[32]
Tertiary waste treatment facility	Able to completely remove COVID-19 virus	Complete deactivation of technologies used	[28]

DO is dissolved oxygen, BOD is biological oxygen demand, COD is chemical oxygen demand, NH_3-N is ammoniacal nitrogen.

2.1. Positive Impacts of COVID-19

With the reduction of industrial, commercial, and other anthropogenic activities associated with COVID-19-restricted movements, lakes, rivers, estuaries, and seas showed improvements in their water quality and biotic life, indicating that humas are actually responsible for their pollution and deterioration. The improvement of water quality and the reduction in fishing pressure provided the opportunity for aquatic animals to multiple at a faster rate compared to the earlier period before the COVID-19 pandemic [33]. Edward et al. [34] reported that water quality parameters such as turbidity, nutrient concentrations, microbial levels, microplastics, dissolved oxygen, phytoplankton concentrations, and fish densities in the southeast Indian coastal ecosystem have improved after the lockdown period associated with COVID-19 pandemic. A decrease in anthropogenic activities including tourism, business and commercial pursuits, agriculture, and industries has decreased discharges into water ways. Selvam et al. [9] reported that the decrease in heavy metals and bacterial loads was due to decreased industrial and agricultural activities, respectively. After the lockdown, Edward et al. [34] reported that macroplastic concentrations from eight locations along coastal area of the Gulf of Mannar, India have decreased from the range of 138–616 items/100 m^2 to 63–347 items/100 m^2. In rivers, Goi [35], and Wang and Xue [36] reported that water turbidity and other water quality parameters improved as the COVID-19 pandemic lockdown provided opportunities for natural self-purification. Similarly, Pinder et al. [37] reported that heavily polluted rivers in India have improved substantially with clean clear waters for the first time in decades. Using remote sending techniques in their study of an Indian lake, Wagh et al. [38] noted a significant reduction in chlorophyll *a*, colored dissolved organic matter, and total suspended solids due low pollution discharges during the COVID-19 lockdown period when anthropogenic activities were restricted, and many large and small scaled industries were closed. In addition, Sun et al. [4] also noted that turbidity levels in Wuhan lakes significantly decreased due to the sharp reduction in human activities after the lockdown.

In addition to the improvement seen in stream and rivers, estuaries and seas also showed some recovery signs. Cherif et al. [39] used satellite imagery to illustrate that the reduction in industrial activities due to the COVID-19 pandemic resulted in the improvement of estuarine and coastal waters of Morocco. In the coastal waters, Mishra et al. [11] reported a decline of chlorophyll *a* and phytoplankton abundance due to the decrease of nitrogen supply from the land area. Shafeeque et al. [40] reported that the strict lockdown resulted in decreases in turbidity and chlorophyll *a* along the coastal areas of India, as decreased human activities reduced the reduction of atmospheric NO_2. Thus, with less pollutants and destruction associated with human activities, the waters in many places became clearer, cleaner, and facilitated self-rehabilitation.

Positive impacts of COVID-19, although transient, allow for insights into the causes and consequences of anthropogenic activities that can be managed through effective regulation and management of eco-resources for the revival of biodiversity and ecosystem health [34,41]. With suitable strategies and commitments adopted by authorities and stakeholders, COVID-19 illustrated that an impaired environment can be efficiently restored.

2.2. Negative Impacts of COVID-19

2.2.1. COVID-19 in Wastewaters

Wastewaters have been reported to contain SARS-CoV-2 RNA that could be transmitted and contaminate the aquatic environment [42]. Kumar et al. [43] suggested that the presence of viral loads in wastewater could indicate that the transmission of SARS-CoV-2 through wastewater is possible, especially in countries where sewer systems are not effective enough in removing the virus. Wastewaters from hospitals and quarantine centers for COVID-19 may contain high concentrations of the viral particles, and, thus, effective treatments of hospital wastewater should be strictly enforced to inactivate the virus and prevent transmission [44,45]. Zhang et al. [19] reported high concentrations of SARS-CoA-2 RNA (0.5 to 18.7 $\times$ 10^3 copies/L) in hospital septic tanks, even after disinfection with sodium hypochlorite (800 g/m^3). Langone et al. [28] reported that SARS-CoV-2 RNA particles were still present in wastewater from secondary treatment plants, but they could be completely removed in wastewater treatment plants (WWTPs) equipped with tertiary waste treatments. Balboa et al. [46] reported that no SARS-CoV-2 RNA was found in well-treated effluent or sludge.

Wastewater contains high concentrations of micro-organisms, organic and inorganic substances that could contribute to the natural degradation of viral RNA [47]. However, Yang et al. [31] reported that sewage sludge in WWTPs could harbor a high abundance of SARS-CoV-2 that could survive for months, as the complex organic matter of the sludge could protect the virus from inactivation. Balboa et al. [46] noted that untreated sewage sludge has high concentrations of viral particles and suggested that thickened sewage sludge was a suitable sampling area for COVID-19 monitoring. Thickened sludge with a high abundance of viral RNA formed a suitable spot for COVID-19 incidence monitoring.

SARS-CoV-2 in human guts, stools, and wastewater form an important fecal-oral route transmission, especially in countries where wastewater treatment facilities are not adequate to remove the viral particles [25,30,48]. Municipal wastewaters in many countries have been used for cleaning, flushing toilets, watering agriculture land, or even for drinking in certain big cities with limited freshwater supply. Thus, the transmission of SARS-CoV-2 RNA via wastewater discharges is a possible route for infection in humans [25]. Zhang et al. [19] reported that viruses in fecal materials in septic tanks can contribute to the spread of SARS-CoV-2 through drainage pipelines. Cervantes-Avil'es et al. [21] reported that SARS-CoV-2 has been detected in wastewater treatment plants, manholes, sewer networks, and various sludge treatment facilities in Europe, North America, South America, and Asia. In fact, the increase of SARS-CoV-2 genetic materials in the wastewater is positively correlated with the number of active COVID-19 patients and can be used as an indicator for the environmental surveillance of the COVID-19 pandemic [43]. Albastaki et al. [20] showed a direct and significant correlation between SARS-CoV-2 viral load in wastewaters and the number of cases in the United Arab Emirates. Gwenzi [25] suggested three main pathways as to how SARS-CoV-2 can be transmitted via the fecal-oral route, all of which are related to the environment (contaminated drinking water), fishery resources (raw or semi-cooked foods from SARS-CoV-2 contaminated waters), or aquaculture products (wastewater-based aquaculture).

The transmission of SARS-CoV-2 via wastewater could eventually contaminate surface waters, as the virus could not be eliminated by conventional secondary treatment of sewage [24]. These viral particles could eventually get to the human through the aquatic food chain and aquatic-based resources such as fish and shellfish [21]. The survival time of SARS-CoV-2 in waters strongly depends on temperature, oxidative chemicals, the concentration of suspended solids and organic matters, and predation along the food chain where SARS-CoV-2 could survive for months in waters with high suspended particles [28,31]. Balboa et al. [46] reported that SARS-CoV-2 has a strong affinity for biosolids. Thus, turbid rivers and lakes with high suspended solids contents are more susceptible to carrying viral particles and form an important route for the viral spread in a community. Wang et al. [49] reported that river hydrology plays an important role in the long transmission route of SARS-CoV-2.

Grossly inefficient wastewater treatment in developing countries could make the waterborne transmission of SARS-CoV-2 a serious threat to the environment and people [45]. Make-shift quarantine centers that do not have adequate facilities for treating SARS-CoV-2 contaminated wastes were commonly used to house thousands of COVID-19 patients, as hospitals were full to the brim. These poor developing countries are at risk, as the absence of proper management of COVID-19 related wastes including wastewater and medical wastes might further spread the virus [1,50]. Adelodun et al. [44] offerred useful suggestions for low-income countries such as use of chlorination, ozonation, and UV radiations to deactivate SARS-CoV-2 in their wastewater and prevent/minimize the COVID-19 outbreaks. In low-income countries, where waste treatment facilities are inadequate to remove the virus, it is very important to ensure that wastes should be disinfected by cheap but effective disinfectant and to prevent the discharge of the wastewater to natural water bodies.

2.2.2. Medical Wastes

With the advent of COVID-19 around the globe, there is a massive surge of medical wastes including plastics, antiviral medicines and drugs, and disinfectants that potentially affect the aquatic environment. With the emergence of COVID-19, there has been an increased use of disinfectants to inactivate the virus on surfaces. DeLeo et al. [18] reported that disinfectant Quat (quaternary ammonium compounds) was commonly used during the COVID-19 pandemic in many countries since it has strong biocidal properties and is effective against bacteria and viruses. Fortunately, the ecotoxicity of this disinfectant is minimized due to its high biodegradation rate and readily absorbed to particles in water and sediment. In addition, chlorine (ClO_2), sodium hypochlorite (NaOCl), or ultraviolet (UV) water treatment can be used, as they are relatively cheap and easily available [24]. However, high doses of chlorine and sodium hypochlorite (~6700 g/m^3) required to completely remove SARS-CoV-2 RNA had high disinfection by-product residual with significant ecological risks [19]. Thus, the ecological risk of disinfection by product residuals needs to be evaluated.

Currently, COVID-19 vaccination is compulsory to acquire immunity against SARS-CoV-2 by minimizing spread, severity, and death. COVID-19 vaccine vials and ancillary supplies are considered infectious material. Therefore, the disposal of these materials also requires standard operation waste treatment procedures. Treatment by disinfecting solution such as chlorine prior to final disposal is necessary to avoid contamination to both humans and the environment. Biomedical waste generated daily is a serious concern, as many would end up in water and act as sources of chemical pollutants or as substrates for viral particles [51]. The increased use of antiviral and antibiotics also results in increased waste of these medicines in water bodies. Nibamureke and Wagenaar [17] reported that medicinal waste could result in impaired fish reproduction. Tarazona et al. [16] developed models to predict the impacts of antibiotics and antiviral drugs on the ecology of aquatic ecosystems and showed sub-lethal effects on fish.

2.2.3. Plastic Pollution

Persistent wastes such as plastic materials become a global pollution problem because they do not biodegrade easily and could be transported to aquatic ecosystems by winds, storm drains, and rivers. These plastic materials undergo fragmentation and break down into smaller plastic particles of difference sizes categorized as mesoplastics (5 mm to 25 mm), microplastics (<5 mm), and nanoplastics (1 nm to 1 μm) through various mechanical, chemical, and weathering processes [13]. Plastic materials submerged in water leached out heavy metals including lead, cadmium, antimony, and copper, in addition to toxic leachable organic substances related to plastic additives and contaminants [52]. Fadare and Okoffo [53] reported an unprecedented rise in the global production of polymer-based face masks (single use), resulting in an increase in microplastics pollution. Many of these toxic pollutants can enter the aquatic food chain, which could accumulate in aquatic foods and transfer to humans. Pan et al. [54] also reported an average of 246 items m^{-3} of microplastics in a Chinese river consisting of PP (polypropene) and PE (polythene) as the major polymers.

With 206.2 million COVID-19 cases and 4.4 million deaths in 220 countries as of the 13 August 2021, billions of pieces of personal protective equipment (facemasks, gloves, aprons, etc.) ended up as waste that could pose as health hazard to the environment and human lives if they are not properly treated and managed. Benson et al. [14] estimated more than 12 billion (equivalent to 105,000 tonnes) medical and fabric masks were discarded monthly in African countries, mainly due to the increased consumption of single-use plastics for surgical masks, medical gowns, face shields, safety glasses, protective aprons, sanitizer containers, plastic shoes, and plastic gloves for the protection from SARS-CoV-2. Ardusso et al. [13] also reported that textile fibers for PPE are impregnated with silver (Ag) and copper (Cu) nanoparticles to reduce the infection and spread of SARS-CoV-2. These antiviral textile wastes are a form of an emerging contaminant with long-term negative repercussions on aquatic environments and biota. Most plastics used in medical applications are made from polypropylene, and the plastic residues are classified as biohazardous materials. Studies by Nzediegwu and Chang [50] and Gwenzi [25] have shown that coronavirus can survive on material surfaces between six to nine days. Aragaw [55] noted that face masks are easily ingested by big animals high in the aquatic food chain such as fishes, turtles, and water birds, with enormous effects on their populations and survival. Humans at the end of the aquatic food chain would have a high risk of eating contaminated aquatic foods. Based on past studies, Latchere et al. [56] illustrated the toxicity of microplastics (MPs) and nanoplastics (NPs) at the species, community, and ecosystem levels, demonstrating the contamination of plastics through the aquatic food chain. Despite the plethora of problems associated with different experiments and analyses, many studies clearly demonstrated the toxicity of plastics in the freshwater-marine continuum, as well as along the trophic transfer. The improper disposal and disinfection of bottles and containers used in healthcare and treatment facilities could be another potential source of viral transmission. Thus, developing countries with poor waste management facilities are at risk.

Microplastic Pollution

The sudden COVID-19 pandemic could exacerbate the microplastic (MP, plastic polymers with <5 mm) pollution, causing more stress to the aquatic environment. The amount of hazardous microplastics in the environment is aggravated by the unprecedented use of face masks and personal protective equipment (PPE) associated with the COVID-19 pandemic [15]. Severini et al. [57] reported that MPs form approximately 95% of the marine litter.

Microplastics enter aquatic ecosystems through industrial discharges, wastewaters, fisheries activities, marine traffic, and other non-point sources from the land and form a major portion of the marine litter. About 97% of plastic residues associated with COVID-19 medical services are incinerated and, in the process, toxic chemicals are released into the environment [15]. Microplastics are a serious threat to aquatic environments, biota, and human health since they are carriers of hazardous contaminants such as heavy metals, polycyclic hydrocarbons (PAHs), and persistent organic pollutants.

The increase of microplastics in aquatic ecosystems due to COVID-19 also has implications for the wild fish stocks and potential health risks from harvested products. The ingestion of microplastics with hazardous contaminants by commercial shrimps posed a serious threat to food security and food safety for humans. In addition, the aquaculture sector is also at risk, especially those in estuaries and coastal areas where a very large input of plastic wastes could accumulate in cultured organisms through the marine food chain. The increase of microplastics in the environment due to COVID-19 could pollute coastal waters, increase ingestion by top predators including commercial species, increase the body microplastic concentration, and increase mortality in shrimps, and, thus, has the potential to affect aquaculture farming [58,59]. Severini et al. [57] illustrated that fibers (identified as polyethylene (PE), polyproplylene (PP), and cellulose) containing several elements (C, O, Si, Al, K, S, Br, Ba, Zn, Ti, and Fe) were ingested by a commercial shrimp, *Pleotocus muelleri*, in a coastal area in the Southwestern Atlantic.

Overall, pathways of plastics to aquatic ecosystems in developed countries are relatively minimal due to well managed and efficient waste management systems. However, poor waste management systems in underdeveloped and developing countries increase the risk of plastics entering water bodies including lakes, rivers, and coastal waters, as they are ill equipped to curb the plastic losses to the environment [60,61]. In addition, leachate from landfills, winds, storms, runoffs, and floods further increase the transfer of plastics from the land source to the aquatic food chains [60].

3. Transmission of COVID-19 to Natural Waters

In countries where raw sewage is directly discharged into natural waterbodies, the likelihood of the transmission of SARS-CoV-2 from wastewaters is very likely. This possible transmission route raises serious concerns, especially in low-income countries where raw wastewater is discharged directly into natural water bodies or through inefficient wastewater treatment plants (Figure 1). The presence of SARS-CoV-2 in natural water has been reported by many studies [9,49]. Guerrero-Loterra et al. [23] reported the presence of SARS-CoV-2 in urban rivers with low sanitation facilities, indicating the transmission of the viral particles from untreated wastewaters and increasing the threat of COVID-19 to the environment and human health. Rimoldi et al. [62] reported the presence of SARS-CoV-2

RNA in treatment plants and in the receiving rivers in northern Italy, demonstrating the danger of inefficient sewerage systems.

Figure 1. Transmission routes of COVID-19 virus to natural water bodies. WWTP = Wastewater treatment plant.

The presence of SARS-CoV-2 in feces and municipal wastewater raised the possibility of it spreading to wider water bodies from insufficiently treated effluent [31]. According to Wartecki and Rzymski [63], the survival of coronaviruses in natural waters depends on water temperature, light, organic matter concentrations, and predation. High water temperature decreased the viral loads due to the denaturation of viral enzyme and protein [51]. Similarly, intense light and high predation would also decrease the viral concentrations in natural waters. However, high organic matter content would enhance the viral particles in natural waters [46,63]. The fate of SARS-CoV-2 RNA in surface waters is dependent on the efficiency of wastewater treatment plants and on potentially inactivating stressors such as sunlight, oxidative chemicals, and predation along the food chain [28]. In addition, Yang et al. [31] also reported that a high abundance of natural microbes could contribute to virus elimination via predation, antagonism, and nutrient competition. Thus, the role of environmentally friendly microbes to eliminate the virus should be further studied and elucidated. In fact, algae have been used to eliminate the virus by inducing the virus to attach to the algal biomass, which could be sedimented and removed [32].

The contamination of surface waters is more common than the ground water, as the latter is deep down in the aquifer and is protected by soil filtration and sediment adsorption mechanism that could remove the virus. However, Selvam et al. [9] reported that there are active interactions between surface waters and the groundwater, indicating that the latter can be seriously infected by SARS-CoV-2 in areas with infected surface waters.

4. Aquatic Ecosystem—Aquatic Foods Coupling

Globally, aquatic ecosystems cover more than 70% of the earth's surface and serve not only to provide provisions such as foods, energy, and medicines but also to provide regulatory and ecological support services that are critical to keeping the world's ecological functions and processes stable and resilient. Thus, ecosystem health is a main factor in the equation of human health and survival. Aquatic ecosystems continuously act as major food suppliers to the human society and contribute to the food security of the world's population, mainly through fisheries and aquaculture industries. However, unsustainable anthropogenic activities, climate change, and unsuspected disasters such as the COVID-19 pandemic could affect this aquatic ecosystems-aquatic foods relationship (Figure 2). Mandal et al. [64] reported that the unavailability of fish supply, a 40% decrease of household purchasing power, and a prolonged COVID-19 pandemic period would affect food security in Bangladesh due to the shortage in supply and the loss of income. In addition, SARS-CoV-2 transmission via contaminated aquatic food species could also affect the demand for aquatic products [65].

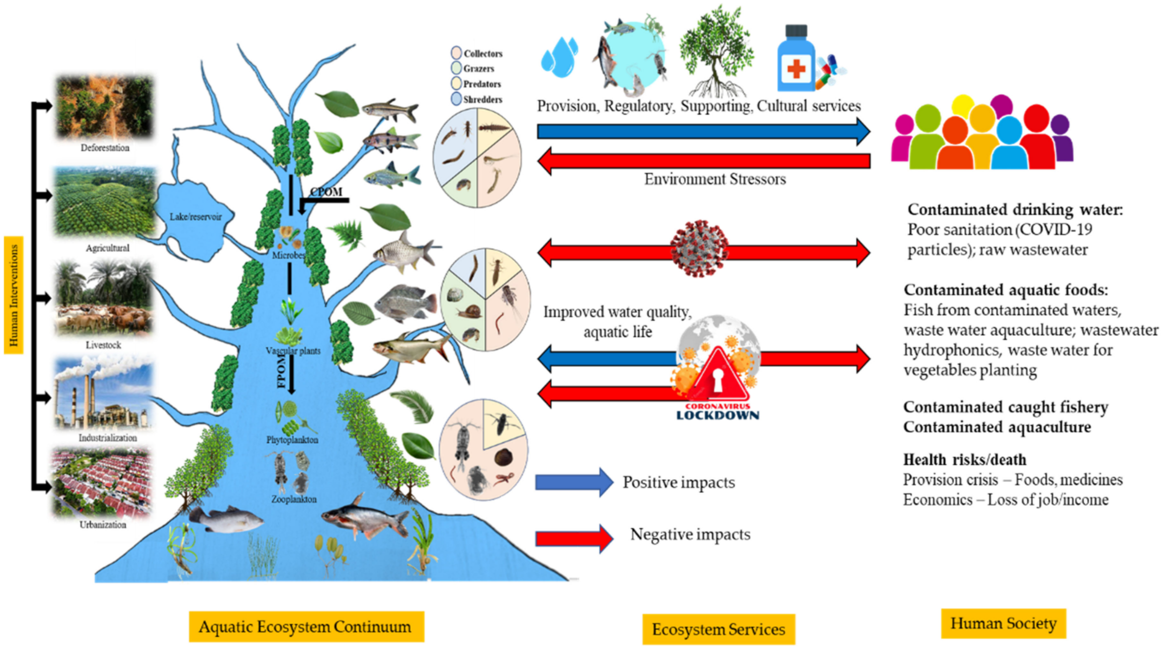

Figure 2. Impacts of COVID-19 on aquatic ecosystem-aquatic resources and human nexus.

In facing challenges from COVID-19, it is important for governments and related authorities to minimize hazardous impacts such as increased microplastic pollution, increased viral transmission and infection, and the loss of income and livelihoods. This is because humans' well-being, livelihoods, and food security during the COVID-19 pandemic depend on adaptive responses and early coping to the disruptive elements along the aquatic-food chain supply at the production, distribution, and trading stages [66]. Fei et al. [67] suggested that assessments, ideas, and experiences in maintaining sustainability and resilience in food systems subjected to the COVID-19 pandemic should be shared globally so that effective responses can be tailored and effectively adapted to local conditions.

4.1. COVID-19 on Fishery and Aquaculture Industries

Capture fisheries and aquaculture are interconnecting sectors, both of which are responsible for food production and supplies. More than 3.2 billion people depend on fish for their animal protein, as the world fish consumption increased from 9 kg per capita in 1961 to approximately 20.3 kg per capita in 2020 [68]. Global fisheries and aquaculture control 35% to 38% of the international supply chain, generating USD 152 billion in exports in 2017 [68]. Most of the global population engaged in fisheries and aquaculture sectors are in Asia (85%), whilst the rest are in Africa (10%) and Latin America and the Caribbean (4%).

The world-wide spread of COVID-19 has serious impacts on water-based industries such as fisheries and aquaculture, affecting socio-economic and ecological systems including food security (Table 2). Like all other agriculture sectors, fisheries and aquaculture industries are subjected to production, distribution networks, and marketing chains. Any disruptions would result in a lack of supply, a loss of jobs and income, and negative impacts on local as well as global economies. Dente and Hashimoto [1] reported that the COVID-19 pandemic resulted in the degradation of global economies and supply chains.

In Southeast Asian countries, including Indonesia, Malaysia, Myanmar, Philippines, Thailand, and Vietnam, fisheries and aquaculture form important economic activities of the littoral communities, which consist mainly of poor and marginal groups (Figure 3). Fishery activities have been affected by COVID-19 in terms of fishing efforts, landings, and marketing, thus directly affecting the livelihood of fishers. The inability to fish and reduced demand are major factors affecting the fishery industry, especially the small-scale fisheries in Southeast Asia [69]. The decrease of activities along the production and marketing chains such as suppliers (fishers), traders, processors, transporters, consumers, and financiers resulted in the collapse of the fishery industry. Small scale fishers were badly affected since their livelihood depends on the daily catch for the rivers and seas. Froehlich et al. [70] suggested the integration of fisheries and aquaculture industries using an ecosystem-based approach as one of the effective approaches to overcome the limited supply of wild-caught sea-food due to the COVID-19 pandemic. In this way, ecological-sociological and economical trade-offs between capture fisheries and aquaculture can be balanced in order to ensure a resilient aquatic foods supply chain [67,70].

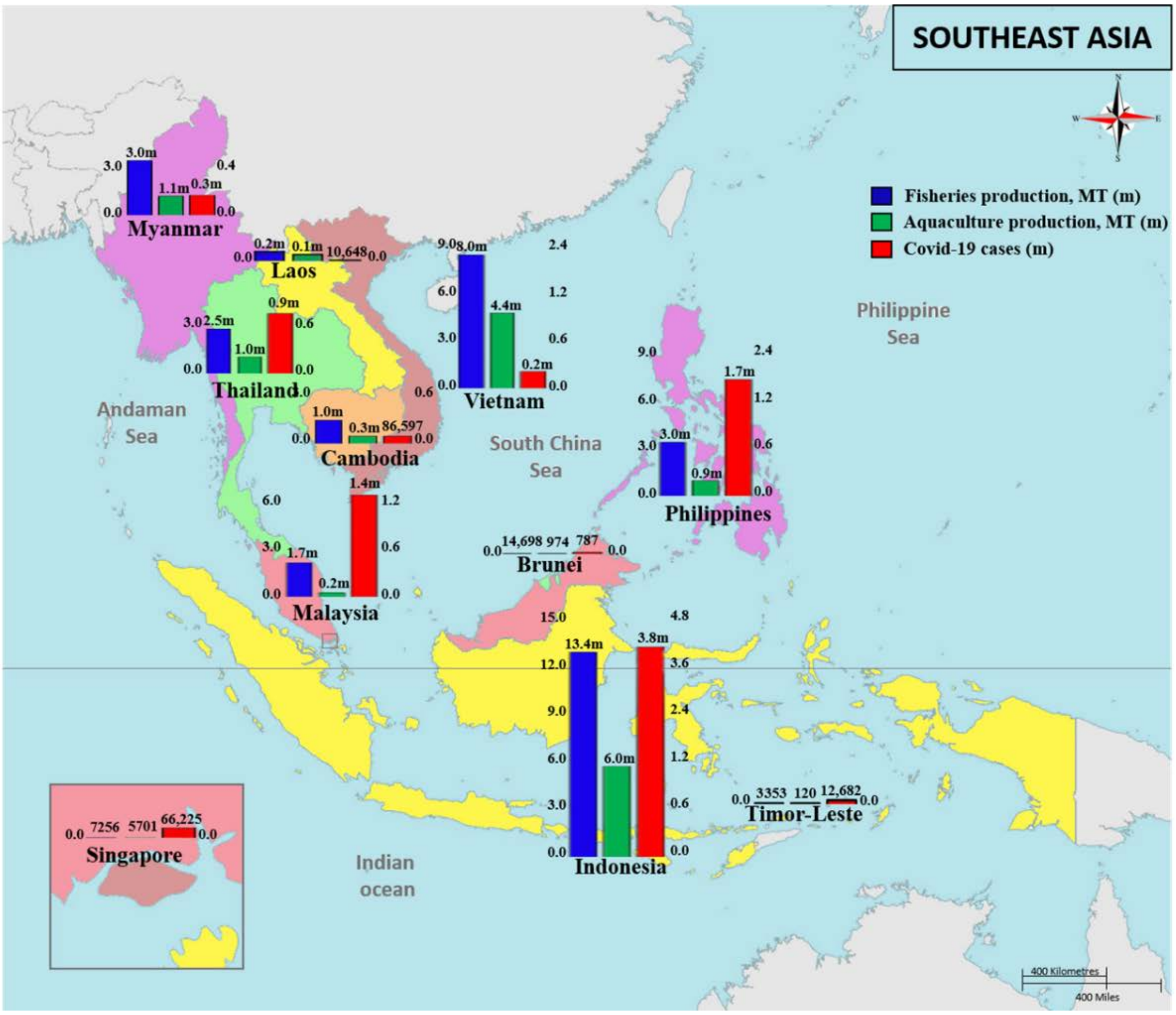

Figure 3. Map indicating the fisheries, industries, and COVID-19 cases in Southeast Asian Countries as of the 15 August 2021.

4.1.1. COVID-19 and Fisheries Industry

Wild fish stocks and their population dynamics and recruitments, which form the main drivers of the capture fisheries industry, are all dependent on the sustainability and resilience of aquatic ecosystems. In turn, fisheries contribute to the food security and livelihood of the human system, providing income and employment to more than 40 million people globally [68]. The COVID-19 pandemic has significantly reduced fishing pressure, providing opportunities for threatened species to recover. Many researchers from United Kingdom [71], Mediterranean [12], Indonesia [69,72], India [34], Africa [73,74], North America [75], and Bangladesh [76] reported that reduced fishing pressure resulted in an increase of wild stocks in inland and marine waters. Even reef fish densities increased substantially due to the COVID-19 lockdown [34]. Smith et al. [77] reported that the declining fishing pressure associated with lockdown periods resulted in increased stocks for some species, but the landing of most commercial species remained the same, probably due to the relatively short lockdown period. In fact, reduced fishing pressure had positive effects only on the fast-growing species, such as deep-water shrimp. However, those positive effects disappeared with the relaxation of the lockdown [12]. Thus, short-term increases of biomass for fast-growing, small-sized organisms during the COVID-19 lockdown period quickly vanished when fishing resumed, indicating that longer periods of non-intervention are needed to allow for ecosystems' complete recovery.

Table 2. Impacts of COVID-19 on fishery and aquaculture industries.

Sector	Components/ Elements	Impacts	Reasons/ Causes	References
Fisheries	Fishing efforts	Reduced 34%	Less fishing operation	[12]
	Landings (fresh catches)	Reduced 40% in USA, 49% (Mediterranean)	Restrictions on social movement and distancing	[12,72,75]
	Revenues; loss of income, loss of livelihoods	Reduced 39%		[12,72]
	Fishing pressure	Reduced fishing pressure—increase of fast-growing species		[12]
	Fish production and sea food value chain	Decrease	Decreased consumer demand, decrease in sales of fish/fish products, decrease in tourism	[12,78,79]
	Fish supply through the value chain	Indonesia—70% decrease of fish supply to commercial sector 40% decrease in domestic consumption		[66,69]
	Decline in exports	Decline by 43% in USA		[75]
	Demand for fish	Malaysia, demand by hotels and restaurant—reduced by 30%, 70% (USA)	Less demand by restaurants	[69,75]
	Income of fishers	Reduced: Indonesian fishers 58%;		[69]
	Illegal fishing	Increase	Lax in enforcement, less surveillance	[78]
	Fishery sustainability	30% of global stocks are below sustainability biological levels	Reduced fishing activity allow fish stocks to recover	[78]

Table 2. *Cont.*

Sector	Components/ Elements	Impacts	Reasons/ Causes	References
Aquaculture	Aquaculture value chain			
	Supply chain	Disrupted supply chain (closure/minimal operation of hatcheries, farms, feed mills, fish/fishery products processing plants)	Difficulties in operation due to inadequate supplies (especially feeds, chemicals, seeds)	[80,81]
	Demand for aquaculture products	Decreased.	Poorer consumers, less demand by tourism industry (hotels, restaurants)	[80]
	Food safety and security	Decreased. Closure of feed mills, fish processing plant	Low inputs and outputs	[81]
	Water quality	Decrease in water quality		
	Microplastics	Increase in mortality of cultures animals	Intake of pollutants	[59]

Although the aquatic systems and their resources showed improvements during the lockdown period, the livelihoods of fishers and the fishery supply chain were negatively impacted by COVID19-pandemic [82]. Coll et al. [25] reported a reduction in fishing pressure (34%), which resulted in a reduction in fish landings (40%) and revenues (39%). In fact, the COVID-19 pandemic has serious consequences for small-scale artisanal fisheries in developing countries that are already vulnerable to changes in fish stocks caused by pollution, over-harvesting, and climate change [83].

Like other food industries, nearly all of the loss of income in the fishery industry was associated with disruptions in the fish supply chain and export markets [72,77]. White et al. [75] reported a decrease of about 40% in fresh fish catches and a 70% drop in consumer demand for seafood in USA. Sunny et al. [76] reported that small scale fisheries and the aquatic food sector in Bangladesh were seriously affected by the COVID-19 pandemic, mainly due to problems with limited fishing activities, labor crises, transportation and logistics, a weak value chain, and a decline in demand. In Indonesia, Campbell et al. [72] reported that the COVID-19 pandemic caused a 90% decline in the number of active fishers and traders, leading to the serious vulnerability of the small-scale fisheries sector in developing countries. In Fiji, the main impact of COVID-19 on small-scale fisheries was the reduction in sales of fish due to decreased local consumption and the decline of the tourism industry [79]. The negative consequences of COVID-19 on lake fisheries in Africa were due to the inability of fishers to access fishing grounds (low fish catches) and the decline in market demand, resulting in less fishing activities and trading and in losses of livelihood amongst inland fishers [73,74]. In fact, Stokes et al. [41] reported that the COVID-19 pandemic posed a higher risk to inland fisheries in 79 countries. In addition, COVID-19 also negatively affected recreational fisheries, a relatively important aquatic-tourism based sector that engaged 10% of the world's population [84].

The impacts of COVID-19 on the fisheries industry are more obvious in poor, developing countries where livelihoods are directly dependent on aquatic ecosystems and they continued to exploit the resources, although illegally [41]. Due to the disruption of trade, the loss of income, and the difficulties of assessing foods, more illegal, unreported, and unregulated (IUU) fishing activities tend to occur [33], especially in developing countries. Pinder et al. [37] noted that long term impacts of COVID-19 on aquatic biodiversity could be devastating, as extreme poverty associated with the pandemic forces people to harvest fish indiscriminately, including those endangered species, using destructive fishing methods such as poisons and dynamites. Thus, the shifting of pressures on aquatic resources and habitats resulted in balanced ecological processes, but the threats from hungry human communities can surpass the original environmental benefits.

Due to the devastating impacts of the COVID-19 pandemic on the fisheries industry worldwide, interventions on policies and actions by authorities are necessary for sustainability in fisheries to contribute to food security and human nutrition [82]. Eggert et al. [85] emphasized the importance of ecology, community, and economics in the development of sustainable fisheries policy to better manage the wild stocks and provide appropriate support for fishery-dependent communities. In lake fisheries, Fiorella et al. [74] suggested that government involvement to control the COVID-19 pandemic and support the small-scale lake fishery in Kenya is important for the recovery from the calamity and the mitigation of future crises. The Malaysian government introduced an economic stimulus package to ease the impacts of COVID-19, especially on the poor communities that make up most of the work force in fisheries and aquaculture sectors [86].

4.1.2. COVID-19 and Aquaculture Industry

With the stagnation of global capture fisheries due to overfishing, pollution, and environmental changes, the aquaculture industry expanded rapidly and currently is the world's fastest growing food production sector, providing adequate protein to the growing global population. Thus, any disruptions in the aquaculture sector would affect the sustainability of food production, supply, and food security (Table 2). Ma et al. [81] reported that aquaculture is vulnerable to COVID-19, which could affect food safety and food security.

Like the fisheries industry, COVID-19 has caused serious disruptions to the supply and marketing chains of the aquaculture industry. Since 90% of world aquaculture is in Asia, the aquaculture industry has been seriously affected by COVID-19 in this region, mainly due to the decrease in local and global demand and the breakdown in the sea-food supply chain [59]. Under pandemic conditions, the closure of food service establishments, the decline in the tourism industry, and stay-home policies mean a significant disruption in the demand and sales of aquaculture and fishery products [87]. Small scale farmers faced difficulties in aquaculture operation due to lack of inputs (feeds, labor), disruption in processing and transportation, and low demand. Small and medium feed mills were forced to close down due to the lack of inputs, labor and expertise. Food and Agriculture Organization of the United Nations (FAO) [80] reported that most feeds mills in Bangladesh had to close down due to difficulties in getting raw materials, the lack of technical expertise, and the lack financial support. Kumaran et al. [88] reported an economic loss of USD 1.5 billion in Indian shrimp aquaculture, with a 40% decline in its export during the first year of the COVID-19 pandemic.

The aquaculture industry, especially intensive aquaculture, requires the close surveillance of water quality and fish health management. Thus, the direct, serious impacts of COVID-19 on the aquaculture industry would be the reduced labor, the disruption of supply lines and logistics that could eventually result in increased disease outbreaks, decreased production, reduced economic resources, and the loss of income [89]. The lack of surveillance could result in the proliferation of toxic dinoflagellate blooms that can cause mass mortalities in cage aquaculture located in rivers, estuaries, or coastal waters [90]. Rodríguez-Benito et al. [91] reported mass fish mortalities in intensive salmonid aquaculture due to harmful algal blooms consisting of toxic dinoflagellates, *Cochlodinium* sp. and *Lepidodinium chlorophorum*, that occurred during the COVID-19 lockdown period resulting in a loss of USD 800 million. Trottet et al. [90] suggested that proper planning and management to adapt to the COVID-19 pandemic are necessary to reduce the impacts of COVID-19 and make food security through the aquaculture industry achievable.

Thus, the significant disruption in farming processes, production, and marketing would translate into a loss of employment and a loss of income due to the COVID-19 pandemic [59,88]. Sarà et al. [92] reported that economic losses in the aquaculture industry depend on the type of aquaculture system, with comparatively lower impacts on those systems with highly diverse products and different market options.

5. Economic Impacts

In the months since the COVID-19 outbreak was first diagnosed, it has spread to about 220 countries in the world. The pandemic has had a substantial impact on global economic growth beyond anything experienced in nearly a century. In developing countries, the COVID-19 pandemic has had significant effects on the countries' economies, leading to the decline of the countries' gross domestic product (GDP). The main causes of economic damage in developing countries are twofold: the first is the consequence from the impacts of the coronavirus around the globe; the second is generated domestically due to the newly imposed movement control order (MCO), or lock-down, by the respective government. In general, COVID-19 has affected not only the eating behaviors of consumers but has also had a massive effect on the capacity to produce and distribute fresh produce. These changes during MCO have slowed down agricultural services such as vegetables, fruits, and the fish and aquatic foods supply chain.

Aquatic Foods Supply Chain and Market

The aquaculture sector supports the livelihood of coastal communities in many countries, particularly those involved in micro- and small-scale fish farming activities. The aquatic food supply chain is a complex system that consists of (1) production, (2) processing, (3) distribution, (4) retailing, and (5) consumption. The impact of COVID-19 has a knock-on effect across all stages of the supply chain. Nevertheless, the processing and distribution are excluded in mostly small-scale operations.

During the MCO, aquaculture production has been slowing down due to limited workforce, decreased demand, the struggle in following the required sanitary measures, and the likelihood of the reduction in animal feed supply due to logistics issues during this pandemic [93]. Most of the aqua-culturists, especially the small-scale, faced difficulties selling their products because of limited sale operations due to the closure of, or the limited operating hours for, the morning and night markets. Consequently, many wholesalers also stopped buying or purchased fewer aquatic products because all the restaurants were ordered to remain closed except for takeaways. Furthermore, disruptions in transportation also caused delays in transporting food products because of the road closures or re-routing during the MCO.

6. Risk of COVID-19 on Aquatic Foods Security

Food security is the composition of two key elements: economic access, or whether the people are able to spend enough money to buy food; and physical access, or whether people have enough scope to find available food. Thus, food security ensures that people have uninterrupted access to food that keeps them satisfied and healthy [94]. However, COVID-19 is now a major global health crisis and has disrupted food systems globally, resulting in significant impacts on economic and food security. In a study by Sunny et al. [76], more than 60% of respondents predicted the COVID-19 pandemic could cause food crises due to ongoing issues associated with economic and physical accessibility. The findings also agreed on the global situation, where 820 million people were more vulnerable with incurable starvation and less access to consume a nutritious diet [95].

The COVID-19 pandemic has revealed major weaknesses, inequities, and system-wide risks in global food security systems. No matter how well managed a system is, there will always be environmental, social, and economic concerns that present a number of risks and hazards to both its development and management and to the aquatic environment and society [96,97].

In general terms, 'risk' is defined as a combination of the likelihood of the occurrence of undesired outcomes and the severity of consequences, while a 'hazard' is the presence of a material or condition that has the potential to cause loss or harm [98]. The concept of risk varies somewhat depending on the sector. Most definitions incorporate the concepts of:

i Uncertainty of outcome (of an action or situation)
ii Probability or likelihood (of an unwanted event occurring)
iii Consequence or impact (if the unwanted event happens)

Risk analysis is thus a pervasive but often unnoticed component of modern society that is used by governments, private sectors, and individuals in the political, scientific, business, financial, social sciences communities, among others.

6.1. Risk Assessment of COVID-19 on Aquatic Foods Security

COVID-19 is a health crisis, but it could also lead to a food security problem if proper measures are not taken (Table 3). The pandemics that the world has experienced earlier have shown that quarantines and panic not only affect human activities and economies [99–101] but also affects the aquatic food systems, which can lead to an increase in hunger and malnutrition. Key activities in a fisheries or aquaculture supply chain for aquatic food security are fishing, aquaculture production, processing, the transport of inputs, distribution, and wholesale and retail marketing. Each of these activities are of equal importance to the success of the supply chain. Each stage of the chain is susceptible to being disrupted or stopped by impacts arising from COVID-19 and related measures [102].

If any link in this food chain is ruptured by the disease or containment measures, there will be associated risk that can affect livelihoods and food security. Risk involves the concept of hazard. Hazard is something with the potential to cause negative consequences. The main hazards in aquatic food security include:

i. Ecological hazards: risk to the aquatic animal or an accompanying organism
ii. Human health/food safety hazards: risk in a "contaminant" in the product
iii. Financial hazard: risk in a decision that might cause business loss or failure

6.1.1. Ecological Hazards

Ecological hazards represent potential sources of harm to human life, health, income, and property and may affect elements of the biophysical, managed, and constructed elements of environments (Table 3). COVID-19 can cause respiratory virus infection through direct and indirect contact. In order to control and avoid the spread of this contagious virus, WHO has advised the public to wear personal protective equipment such as face masks and gloves [103]. Additionally, there is a lack of information on how to properly dispose of the used face masks and gloves. This problem worsens by inadequate disposal facilities to deal with the biohazardous materials, and this is a great risk that can impact the marine environment and human health as a new form of marine pollutant that could contaminate the aquatic products [104].

The increase of single-use plastics during the COVID-19 pandemic is also inevitable. Frontliners use plastics as their protective gear, and people use plastic containers for take-away foods. Many grocery stores and restaurants have also prohibited their customers from bringing their containers or shopping bags to avoid cross-contamination. This situation will increase the risk of plastic pollution in the aquatic environment in the long-term.

Table 3. Risk summary of COVID-19 on Aquatic Foods Security.

Sector	Hazard	Risk	Risk Mitigation	References
Fisheries	Ecological hazards	Excessive and erratic use of chemical disinfectants around the globe post-COVID-19, as well as its long-term impact on human exposure and water contamination	Proactive policies and regulatory frameworks	[105]
Fisheries	Ecological hazards	Lack of information on how to properly dispose the used face masks and gloves can impact the marine environment	Proactive policies and regulatory frameworks	[106,107]
Fisheries	Ecological hazards	Inadequate disposal facilities to deal with the biohazard materials that can impact the marine environment and human health as a new form of marine pollutant	Proactive policies and regulatory frameworks, good management practices, good manufacturing practices (GMP)	[106–108]
Fisheries	Ecological hazards	The increase of single-use plastics during the COVID-19 pandemic will increase the risk of plastic pollution in the aquatic environment	Proactive policies and regulatory frameworks, good management practices, good manufacturing practices (GMP)	[107,109]
Fisheries	Human health/food safety hazards	Aquatic food being associated with transmission of COVID-19	National strategies on aquatic animal health, biosecurity, disease surveillance and reporting, early warning, emergency response and contingency planning, import risk analysis, good health management practices, vaccination, GIS risk mapping	[110,111]
Fisheries	Human health/food safety hazards	Face masks and derived micro-particles are easily ingested by fish and other aquatic life organisms, which will affect the aquatic food chain	Good management Practices, good hygienic practices (GHP), good manufacturing practices (GMP), food safety controls, consumer education, integrated approaches involving health education, vector control and selective population chemotherapy (for parasitic infections)	[55,107]
Fisheries		Pharmaceuticals compounds from different classes used to treat the patient with coronavirus infection increase the level of pharmaceutical residues that might infuse into the aquatic environment	Good management practices, good hygienic practices (GHP), good manufacturing practices (GMP), food safety controls, consumer education, integrated approaches involving health education, vector control and selective population chemotherapy (for parasitic infections)	[107,112]

Table 3. *Cont.*

Sector	Hazard	Risk	Risk Mitigation	References
Fisheries	Financial hazard	Reduction of seafood in national and global demand and the breakdown of fish supply chains	More automation, digitization, using traceability tools to facilitate trade	[113,114]
Fisheries	Financial hazard	Fish consumption per household has been reduced significantly during the pandemic.	More automation, digitization, using traceability tools to facilitate trade	[64]
Aquaculture	Ecological hazards	Decreases in inputs (i.e., feeds, seeds, aerators, fish health products) availability and accessibility due to movement restrictions	Stocked relevant input in advance, leveraging existing relationships with suppliers, negotiations.	[115]
Aquaculture	Human health/food safety hazards	The presence of SARS-CoV-2 on frozen aquatic food animal species or their products, including their packaging materials and storage environments	Good management practices; good aquaculture practices (GAP); good hygienic practices (GHP); good manufacturing practices (GMP); food safety controls; consumer education; integrated approaches involving health education, vector control and selective population chemotherapy (for parasitic infections)	[116,117]
Aquaculture	Financial hazard	Reducing or halting business operations, and laying-off or hiring fewer temporary workers to cope with financial strains	More automation, digitization, using traceability tools to facilitate trade	[102,107,115]
Aquaculture	Financial hazard	Changes in food consumption and difficulties in reaching consumers	More automation, digitization, using traceability tools to facilitate trade	[118]

6.1.2. Human Health/Food Safety Hazards

Food safety deals with safeguarding the food supply chain from the introduction, growth, or survival of hazardous microbial and chemical agents. Food safety hazard is an important issue, as many countries are increasingly interdependent on the availability of their food supply and on its safety. With the advent of the COVID-19 pandemic and its potential impacts on food safety and human health, food production should be done safely to maximize public health gains and environmental benefits.

The use of pharmaceuticals and drugs to combat the COVID-19 pandemic is also unavoidable. Pharmaceutical compounds from different classes such as chloroquine, hydroxy chloroquine, azithromycin, remdesivir, lopinavir, ribavirin, and ritonavir have been widely used to treat the patient with coronavirus infection [119,120]. Therefore, there is a risk in the level elevation of pharmaceutical residues that might infuse the aquatic environment due to the increasing number of pharmaceuticals and drugs used in medical facilities. Several sources have been linked with the contamination of these residues in aquatic products, including hospital wastes [121].

6.1.3. Financial Hazards

In the COVID-19 pandemic period, many households would experience financial distress resulting in reduced spending and decreased demand. This situation will then affect production, processing, and distribution and will cause disruption in domestic and international supply chains. Mandal et al. [64] found that approximately 80% of their respondents reported reduced income, and a quarter of respondents lost their jobs between March and June 2020. The frequency of fish consumption, an essential component of Bangladeshi diets, was significantly reduced during the pandemic. Azra et al. [107] reported that COVID-19 had a profound impact on aquaculture activities in Malaysia. The main factor affecting aquaculture industry was the sale decrease, followed by a decrease in the price of cultured animals due to oversupply, which was driven by low demand. The closure of fish mills, hatcheries, farms, and postharvest processing plants could further increase the financial hazard to the food security.

7. Mitigation Measures and Technologies

The positive and negative impacts of COVID-19 on the aquatic ecosystem-aquatic foods-human nexus provide many useful experiences and lessons that can be used to develop effective policies and strategies in minimizing the impacts of similar crises in the future. The improvement of water quality due to the decrease of human activities during the COVID-19 lockdown proved beyond doubts that management tools are available to ensure sustainable anthropogenic activities with minimal environmental impacts. The COVID-19 pandemic also highlights that fact that transformation and integrated solutions in various aspects based on research and innovation can be reached within a shorter time frame if carefully planned and implemented [122]. Major approaches in mitigating measures include managing the source and transmission of the virus, managing the resources, and effective adaptations in terms of human behavior and the socioeconomics of the communities.

Technologically, water is an effective medium to spread bacteria and viruses including SARS-CoV-2. Adelodun et al. [44] suggested separating the wastewater treatment of the health care facilities from the community central systems for the proper treatment of the COVID-19 virus. Sewage sludge that could harbor a high concentration of viral particles should be dewatered and sterilized in a well-mixed tank to ensure complete inactivation, since high organic matter in the sludge could protect the virus from disinfectant [31]. For an effective centralized disinfection with chlorine, the residual concentration of free chlorine should be more than 0.5 mg/L after at least 30 min of contact time at $pH < 8.0$. A chlorine residue must be maintained throughout the distribution system. Mohapatra et al. [30] reported that complete inactivation of SARS-CoV-2 by chlorination is possible and suggested that the removal of the viral particles can be done by coagulation-flocculation and filtration. Other methods for COVID-19 virus removal include filtration (particle, microfiltration, ultrafiltration, nanofiltration), coagulation, and reverse osmosis that uses a variety of substances such as gravel, sand, ceramic, polymers, membranes, and nanomaterials [31].

Thus, efficient sanitation management is one of the most important approaches to control the spread of the virus through transmission from sewage to natural water bodies. Sewage surveillance should be effective enough to ensure no transmission between wastewaters and surface waters, especially those water bodies used for water supplies [24]. Wastewaters should also be prevented from contaminating natural waters used for fisheries and aquaculture activities, as the virus can be transmitted to humans through fishery products [24]. Celis et al. [15] suggested that biodegradable plastics that are free from toxic chemicals should be developed and used to avoid contaminating the environment and protect human health.

Interventions from the governments in low-income countries to ensure access to basic life necessities related to water, foods, and sanitation during the COVID-19 pandemic are necessary to prevent further spread of the disease [7,50]. Interventions by local and national authorities in protecting fisheries and aquaculture industries to overcome difficulties during the pandemic are also needed, especially in developing countries [76,77].

7.1. Monitoring

The surveillance and monitoring of causes, symptoms, and consequences of the COVID-19 pandemic are essential to mitigate its devasting global impacts on aquatic ecosystems and human health. The use of novel and effective technologies for the early and rapid detection and quantification of the virus and the effective treatment of wastewater for viral removal are necessary for mitigating the impacts of the pandemic [21,29]. Investigations involving material flow analysis, life-cycle assessment, network analysis, and input-out evaluation are important to fully understand the consequence of COVID-19 pandemic [1]. Tarazona et al. [16] suggested monitoring the medical waste in waterbodies since antibiotics and antiviral drugs used for COVID-19 patients were observed to cause sublethal effects in fish.

The monitoring of SARS-CoV-2 RNA in wastewaters can be one of the most useful monitoring tools of the pandemic for a reliable public health response, since the wastewater contains excrements from both symptomatic and asymptomatic individuals [22,26,27,43,123]. Lu et al. [27] supported the fact that the total number of viral RNA copies in infected fecal materials and wastewaters are important for highly sensitive, accurate, and reliable approaches in detecting RNA for wastewater-based epidemiology (WBE). Thus, the use of effective concentration methods involving PEG (polyethylene glucol)-based separation, electrostatically charged membrane filtration, and ultrafiltration is necessary prior to RNA extraction and RT-qPCR (real-time quantitative polymerase chain reaction) detection. Randazzo et al. [42] and Albastaki et al. [20] showed that WEB was cost effective for COVID-19 epidemiological surveillance, as the detection of the viral load in the wastewater for SARS-CoV-2 was earlier than that detected in patients. Tiwari et al. [124] suggested a framework for the surveillance of wastewater for early epidemic prediction (SWEEP) for the effective implementation of WBE. In sub-Saharan Africa, where sanitation is very poor and where there is high usage of open latrines, the surveillance of SARS-CoV-2 in wastewater is essential to controlling the widespread of COVID-19 [125]. Thus, WBE can be used as a early warning system and as a pre-screening tool to better target testing needs in certain communities with no/limited resources [47,126]. To make the technology more applicable, Saththasivam et al. [127] developed a mathematical model based on SARS-CoV-2 RNA wastewater epidemiology (WEB) to assess the COVID-19 trend in a given population.

In addition to WBE, the application of GIS (geographic information system) and spatial statistics can be used to monitor the spatial spread of COVID-19 [128]. Chen et al. [129] used a Bayesian spatial-temporal model to determine the distribution of COVID-19 cases and its correlation with the migration of the Wuhan population in the early stages of the pandemic in China, which was effective for early warning and the prevention of future outbreaks. Later, Tang et al. [130] used Poisson's segmented model to provide further explanations for the real time analysis of the changing patterns in different geographical areas of the country with the temporal evolution of the COVID-19 epidemic. Desjardins et al. [131] improved the surveillance tool by using prospective space-time statistics to identify active and emerging COVID-19 groups and to control the disease outbreak. The ability to add updated COVID-19 counts, re-execute the statistics to identify new emerging groups, and track previously detected groups to determine whether they are growing or shrinking in magnitude could provide important information for decision-making by relevant authorities to contain the spread of COVID-19.

Additionally, the use of remote monitoring stations to monitor extremely hazardous and remote settings are enabled by using IoT (internet of things) technology. Tracking and contact- tracing using IoT technologies have shown that it is possible to reduce the spread of COVID-19 in communities. Flying IoT based Unmanned Aerial Vehicles (UAVs) represent an example of video surveillance collected by drones that can be used for surveillance and monitoring without having to risk physical contact.

For the monitoring of ecosystem events, Rodríguez-Benito et al. [91] demonstrated the use of satellite technology for the monitoring of harmful algal bloom in aquaculture areas during the lockdown period as an early warning system to prevent mass fish mortality. Remote sensing-based observation also shows promise, as it measures TSS (total suspended solids) concentrations in natural waters with high spatial and temporal resolutions that can cover all the scales of variability and identify the spatiotemporal extent of TSS [132,133]. Miller and McKee [134] utilized the MODIS (moderate resolution imaging Spectroradiometer) red band to investigate TSS based on a relationship between the band and in-situ samples in the Gulf of Mexico. This approach could be applied to other coastal/inland regions because of the robustness of the relationship. Other related algorithms were also developed to monitor environmental changes in aquatic ecosystems [135,136].

7.2. Mitigating Impacts on Aquatic Food Producing Industries

To reduce the vulnerability of fisheries and aquaculture industries to global shocks, attention to the diversity of species and products, a resilient approach to manage local food systems, and effective governance should be in place to minimize impacts, attain rapid recovery from pandemics, and maintain the socio-economical-ecological resilience [137]. Fishers can also adapt by practicing backyard aquaculture to grow fish and shrimps. Appropriate policy measures and interventions by the respective governments to minimize the impacts of COVID-19 on fisheries and aquaculture sectors are necessary [59,107].

Most farmers should receive economic stimulus packages from their governments and related agencies to lessen the disruptions and losses so that they can adapt and minimize the impacts of COVID-19. Kumaran et al. [88] reported that the Government of India provided incentives and an economic package with adequate technical and policy measures to ride over the impact of COVID-19 and ensure the sustainability of the aquaculture industry in the country. In their study on the impacts of COVID-19 on the aquaculture industries in 47 countries, Sarà et al. [92] suggested that the detrimental impacts of COVID-19 should be assessed together with other anthropogenic stressors to maximize the long-term resilience of the aquatic food industry.

Love et al. [66] and Dobrowolski et al. [138] suggested that past lessons and effective adaptive responses are necessary to cope and minimize the impacts of COVID-19 while preparing for future shocks. Given the high level of the diversities and complexities of the aquatic environment-resource-human nexus, no single approach can effectively achieve the sustainable aquatic resources worldwide. Thus, responses to the COVID-19 crisis should be translated and adapted to the local context, as no one-size-fits-all approach is appropriate. Cooke et al. [33] reported that the impacts of the COVID-19 pandemic on fish biodiversity are mixed, depending on localized socio-economic status and governments' interventions. Thus, responses should be in tandem with the local situations.

8. Conclusions

Reduction in unsustainable anthropogenic activities associated with COVID-19 lockdowns resulted in healthier aquatic ecosystems with better water quality and better aquatic productivity. With less pollutants and destruction associated with human activities, aquatic ecosystems were healthier and showed signs of self-rehabilitation. If these conditions persist, ecosystem services will be stable and resilient to support aquatic food production, with long term ecological and socio-economic benefits to human society. With suitable strategies and commitments adopted by authorities and stakeholders, COVID-19 illustrated that an impaired environment can be efficiently restored. However, temporary improvements of aquatic habitats to increase biodiversity and the production of slow-growing species were unlikely to exhibit long-term changes due to the relatively short time scale.

Negative impacts of COVID-19 associated with wastewaters, pharmaceutical wastes, disinfectants, and microplastics masked the positive benefits, caused devastating social and economic impacts worldwide, and presented unprecedented mammoth challenges to the global human society. The increased use of disposal plastic items and personal protective equipment during the COVID-19 pandemic has resulted in enormous plastic waste worldwide and increased microplastic pollution in the aquatic environment, especially in developing nations with limited waste treatment infrastructure. The risks of COVID-19 outbreaks were high, as viral transmission could occur from sewage treatment plants to natural waters, aquatic food chains, and humans, especially in poor developing countries where sewage treatments were still inadequate to eliminate the virus. The potential of SARS-CoV-2 transmission via wastewater was more prone in low-income countries with poorly developed health, sanitation, and wastewater treatment facilities. The ecological risks of medical wastes, microplastic pollution, and disinfection by-product residuals in aquatic environments were high and needed to be improved to avoid harmful effects on ecosystems and human health.

Fisheries and aquaculture play enormous roles in food security worldwide, providing a major source of animal protein worldwide. However, the periodical lockdowns due to the waves of the COVID-19 pandemic have seriously affected these aquatic food supply chains, including disruptions in production, distribution, trade, and marketing, resulting in the loss of livelihoods and income for those in related sectors. Interventions from authorities are needed to address the challenges associated with the COVID-19 pandemic in order to protect the natural environment and livelihoods, create jobs, and boost economies. Effective measures to facilitate fishers and aquaculture farmers in their production and trading are needed, while ensuring the implementation of disease monitoring and surveillances, biosecurity, and health standards to protect the people and ecosystems. Fishers and fish farmers require government support/intervention to ensure a smooth value chain and financial incentives/packages to continue operation, sustain their businesses, and avoid bankruptcy. Governments and fishery authorities should be prepared to address calamities such as the COVID-19 pandemic by collecting adequate information and data to provide guidance in establishing policies and appropriate interventions to minimize the impacts.

More studies are needed to understand the impacts of the COVID-19 pandemic on the ecology and socio-economy of human communities. The roles of sustainable aquatic ecosystems and resources are critical to preventing the collapse of fisheries and aquaculture industries in developing countries. Some key features that can be considered for mitigating impacts include the long-term management of the aquatic environment and its resources, the protection of biodiversity, the effective mitigation of disruptive elements, economic stimulus for the recovery for aquatic-based industries, and good governance for ecosystem-based management. Various assessments on the vulnerabilities and opportunities in fisheries and aquaculture industries provide measures for adaptations and mitigation that would be valuable for the sustainability and resiliency of these water-based industries to face future global pandemics and other devastations.

Author Contributions: Conceptualization, F.M.Y. and A.F.A.; writing—original draft, F.M.Y., A.F.A. and W.A.D.U.; review and editing, F.M.Y., A.F.A., A.Z.A. and W.A.D.U. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the Universiti Putra Malaysia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data presented in this study are available through digital object identifiers/reports listed in the reference list.

Conflicts of Interest: The authors declare no conflict of interest.

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