

Original Research Articles

Environmental Impacts of Aquaculture in the Philippines

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Aquaculture is one of the fastest-growing industries globally, hailed as a crucial source of aquatic food for human consumption. In the Philippines, a nation with a significant stake in global aquaculture, this sector not only supports food security and provides livelihoods but also boosts the national economy by generating valuable export revenue. However, the rapid expansion of aquaculture in the country has sparked concerns, particularly regarding its environmental footprint. This work critically reviews the environmental impacts of aquaculture in the Philippines by reviewing available literature published from 1918 up to the present on the environmental impacts of Philippine aquaculture using relevant keywords from databases like Scopus, Web of Science, PubMed, Google Scholar, and ResearchGate, and some Philippine government databases like the Philippine Statistics Authority and Bureau of Fisheries and Aquatic Resources. While aquaculture plays a key role in ensuring food security, sustaining livelihoods, and supporting the country's economic growth, it has also been linked to several environmental issues. These include the destruction of mangrove habitats, degradation of seagrass ecosystems, sediment disruption, water pollution, and declining water quality. Moreover, the presence of antibiotic-resistant genes and residues in farmed species, alongside the introduction of non-native species, has triggered biodiversity imbalances and ecosystem degradation. This review underscores the urgent need for mitigation strategies to address these environmental impacts and proposes actionable solutions. Looking ahead, the future of Philippine aquaculture will depend on how well it balances growth with sustainability, ensuring the sector's continued contribution to the economy and the environment.

INTRODUCTION

As the global population expands, the demand for aquatic food products surges. Aquaculture, a rapidly growing sector, offers a sustainable solution by providing nutrient-rich seafood, supporting economic development, and contributing to food security.¹⁻³ Aquaculture's global significance is underscored by its recent milestone: in 2022, it surpassed capture fisheries as the leading producer of aquatic animals, reaching a record high of 130.9 million tonnes.⁴ Among the contributors to global aquaculture, is the Philippines.

Aquaculture in the Philippines has emerged as a pivotal force within the nation's fisheries sector. Its substantial contribution to fish production has significantly impacted the country's food security, providing a vital protein source for its vast population. Each Filipino consumes an average of 34 kg of fish annually, which constitutes a remarkable 12% of their total protein intake.⁵ Beyond its nutritional significance, the aquaculture sector supports the livelihoods of millions of Filipino fisherfolk.⁶ The sector's production volume (over 2 million metric tons, MT) has witnessed a steady upward trajectory in recent years, reflecting its growing importance in the country's economy.⁷

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Aquatic food products in the Philippines are mainly produced by aquaculture, surpassing the contribution from the capture fisheries sector.⁶ The main cultured aquatic organisms are seaweeds (primarily *Eucheuma* and *Kappaphycus*), tilapia (*Oreochromis* spp.), milkfish (*Chanos chanos*), prawn/shrimp (*Penaeus*, *Metapenaeus*, *Macrobrachium* spp.), and shellfishes (*Crassostrea*, *Perna*, and *Modiolus* spp.).^{7,8} To address the increasing demand for these aquaculture organisms, farming intensification has been inevitable.^{6,9,10}

However, the burgeoning aquaculture sector in the Philippines, while contributing to economic growth, has simultaneously generated apprehensions regarding its ecological footprint.^{11,12} A primary deleterious consequence is habitat obliteration. The proliferation of aquaculture frequently necessitates the transformation of coastal ecosystems, including mangrove forests and seagrass meadows, into artificial cultivation ponds.^{13,14} This ecological disruption can instigate coastal erosion, biodiversity diminution, and diminished coastal protective capacity. Furthermore, the degradation of water quality poses a substantial challenge. Aquaculture operations can introduce pollutants into aquatic environments, such as excess nutrients, organic waste, and antimicrobial agents. Nutrient enrichment can trigger eutrophication, resulting in algal blooms and subsequent oxygen depletion. The sector's influence on marine biota is also noteworthy. Additionally, the introduction of exotic species, habitat destruction, and the exploitation of wild fish populations for aquaculture feed can all contribute to biodiversity decline. Moreover, the prophylactic use of antibiotics in aquaculture can foster the proliferation of antibiotic-resistant bacteria, potentially jeopardizing public health.^{6,15-20}

To date, there are limited studies that synthesize the environmental impacts of aquaculture activities in the Philippines, and the available literature is scattered. Therefore, this work provides a comprehensive review of the existing literature on the environmental impacts of Philippine aquaculture while also providing a quick overview of Philippine aquaculture. Specifically, this review examines the impacts on marine habitats (mangroves and seagrasses), biodiversity, sediment disturbance, water pollution, declining water quality, and the presence of antibiotic-resistant genes and residues. This study reviewed literature published from 1918 to the present, using keywords such as aquaculture, antibiotic use, antibiotic-resistant genes, aquatic, biodiversity, chemicals, decline, disease, effects, environmental impacts, fish kills, fisheries, habitat, IMTA, tilapia, mangroves, milkfish, mitigation, seaweeds, sea ranching, seagrass, shrimp, oxygen depletion, Philippines, pollution, production, and water quality. The literature was sourced from databases including Scopus, Web of Science, PubMed, Google Scholar, and ResearchGate and some Philippine government databases like the Philippine Statistics Authority and Bureau of Fisheries and Aquatic Resources. Furthermore, to address the identified environmental impacts, various recommended mitigation strategies are explored and presented. This paper also discusses future prospects and outlooks, aiming to foster a resilient and responsible aquaculture industry that enhances

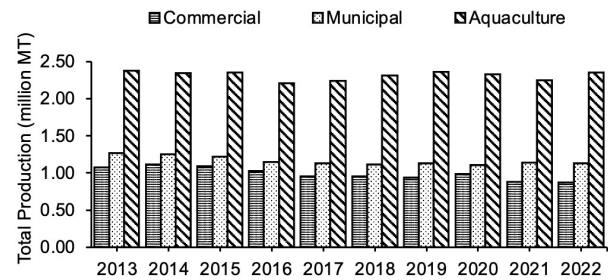


Figure 1. Fisheries Production of the Philippines from 2013 to 2022.^{7,8}

both national food security and environmental stewardship within the Philippines.

OVERVIEW OF AQUACULTURE IN THE PHILIPPINES

In 2022, Philippine aquaculture production sustained its growth trajectory, culminating in 2.35 million MT.⁸ This output constituted 1.02% of the global aquaculture yield of 90.86 million MT. Concurrently, the nation's seaweed production reached 1.34 million MT, representing 3.82% of the global total of 36.31 million MT. The aggregate estimated farm gate value of these aquaculture commodities attained USD 2.14 billion. These statistics reaffirmed the Philippines' standing as the 11th-largest producer of aquatic animals and the 4th largest seaweed cultivator globally. Moreover, the Philippines' per capita apparent consumption of aquatic foods reached 28.9 kg year⁻¹ in 2019.²¹ While marginally below the most recent domestic per capita fish consumption estimate of 34 kg year⁻¹,^{8,22} the crucial role of the fisheries and aquaculture sector in ensuring global food security and satisfying the escalating demand for nutritious sustenance is widely acknowledged.^{21,23}

PHILIPPINE AQUACULTURE PRODUCTION

In the Philippines, fisheries continuously play a dynamic and crucial role in providing food production available to consumers. These productions come from commercial fisheries, municipal fisheries, and aquaculture sectors.^{6-8,24} Over the past decade (2013-2022), aquaculture has consistently outpaced capture fisheries, consistently yielding over 2 million MT (Figure 1). Municipal fisheries have maintained a relatively steady production of around 1 million MT, while commercial fisheries have experienced a gradual decline, falling below 1 million MT.^{7,8}

CULTURE ENVIRONMENTS, CULTURE SYSTEMS AND MAJOR COMMODITIES

In the Philippines, aquaculture, with a long and intricate history, encompasses a diverse array of species cultivated in complex aquatic environments. Although the exact origins of aquaculture in the country remain obscure, it is widely believed that the earliest fishponds were established

Table 1. Aquaculture production based on culture system and environment, 2022 (in MT)

Environment	Culture System					
	Fishpond	Fish cage	Fish pen	Mariculture	Small Farm reservoir	Rice-Fish
Brackishwater	297,513.98	1,728.88	16,433.48			
Freshwater	182,225.13	54,164.02	25,440.56		175.21	14.95
Marine water		175,117.49	547.68	1,595,890.63		
Total	479,739.11	231,010.39	42,421.72	1,595,890.63	175.21	14.95

Source: PSA⁷; BFAR⁸

for brackish water milkfish cultivation, relying solely on natural food sources.²⁵ Over time, milkfish culture evolved into a sophisticated art, incorporating various methods of cages, pens, and pond systems.²⁵ Beyond milkfish, the literature on rural aquaculture in the Philippines highlights the cultivation of numerous other species, including freshwater carps and its other introduced species, oysters and mussels, penaeid shrimp, mangrove crab, tilapia, seaweeds, giant freshwater prawn, rabbitfish and spadefish, and carnivorous species like seabass and grouper.²⁵

Based on 2022 production data (Table 1), fishponds, fish cages, fish pens, and mariculture are the predominant culture systems employed in freshwater, marine, and brackish-water environments. Marine environments have yielded the highest production, primarily from mariculture and fish cages, totaling 1.7 million MT, comprising seaweeds, milkfish, shellfish, groupers, siganid, and spiny lobster. Brackish-water environments, primarily utilizing fishponds and fish pens, have contributed nearly 300 thousand MT, predominantly consisting of milkfish, tilapia, crustaceans, siganid, and groupers. Freshwater environments have recorded a production of 261 thousand MT, primarily comprising tilapia, carp, milkfish, catfish, gourami, freshwater prawn, and mudfish cultivated in fishponds, fish cages, and fish pens.^{7,8}

Regarding culture systems, mariculture has produced nearly 1.6 million MT, while fishponds have accounted for approximately 0.5 million MT in both brackish and freshwater environments. Fish cages have contributed 0.2 million MT across all environments, and fish pens have produced 42 thousand MT. Smaller-scale freshwater cultures, such as small farm reservoirs and rice-fish systems, have yielded 124 and 14 MT, respectively.^{7,8}

Bureau of Fisheries and Aquatic Resources⁸ emphasized the leading five aquaculture commodities based on reported volume and value (Table 2). These commodities include seaweeds, milkfish, tilapia, shrimp/prawns, and shellfish. In terms of production volume, seaweeds (*Kappaphycus* and *Eucheuma* spp.) dominated, contributing 65.76% or 1.5 million MT. Milkfish (*Chanos chanos*) ranked second with 16.51% or 300 thousand MT, followed by tilapia (*Oreochromis* spp.) at 10.72% or 200 thousand MT. Shrimp (*Penaeus* spp., *Metapenaeus* spp., *Macrobrachium* spp.) and shellfish (*Crassostrea* spp., *Perna* spp., *Modiolus* spp.) comprised smaller proportions, contributing 2.99% (70 thousand MT) and 2.17% (50 thousand MT), respectively. The 1.84% (50 MT) aggregated volume of production for other commodities. However, despite their substantial volume,

seaweeds ranked fourth in terms of value, contributing only USD 292 million or 13.39%. Milkfish, on the other hand, held the top position with USD 817.6 million or 37.42%. Shrimp/prawns followed with USD 486.3 million (22.29%), tilapia with USD 377.2 million (17.29%), and shellfish with USD 18 million (1.13%). The USD 185 million (8.56%) shared by the other aquaculture values.

In terms of export volume and value, seaweeds, milkfish, and shrimp/prawns were the leading aquaculture commodities in foreign trade, with the top 10 countries of export destinations (Table 3). Seaweeds and their products (carrageenans) registered the highest exported volume of 48,891 MT, valued at USD 349 million, representing 28.8% of total fishery exports. The principal destinations included China, the United States of America, Spain, the Netherlands, Germany, Brazil, Mexico, India, Australia, and the United Kingdom of Great Britain and Northern Ireland. Milkfish exports totaled 6,661 MT, valued at USD 37 million (2.4%), with the United States of America, Canada, Australia, Qatar, United Arab Emirates, Guam, the United Kingdom of Great Britain and Northern Ireland, Thailand, the Netherlands, and South Korea as the major markets. Shrimp/prawn exports reached 3,309 MT, valued at almost USD 20 million (1.6%), with Japan, the United States of America, Taiwan, Hong Kong, France, South Korea, Australia, Guam, Vietnam, and Lebanon.^{7,8}

Together, seaweeds, milkfish, tilapia, shrimp/prawn, and shellfish accounted for 98.15% of the total aquaculture production volume and 91.52% of the total value, with milkfish being the dominant contributor. Tawi-Tawi in the Bangsamoro Autonomous Region in Muslim Mindanao (BARMM) led seaweed production, contributing 40.59%, followed by Palawan and Sulu. BARMM emerged as the nation's leading seaweed region with a 66.07% share. Pangasinan in Region 1 was the top producer of milkfish, followed by Capiz and Pampanga. Batangas in Region 3 is dominated by tilapia production, contributing over half of the national total. Pampanga also led shrimp/prawn production, followed by Sarangani and Negros Occidental. Bulacan in Region 3 was the leading producer of shellfish, followed by Capiz and Cavite.^{7,8}

Table 4 outlines the various types of aquaculture systems, their environments, the total number of aquafarms, and the total areas they occupy. According to PSA,²⁶ the highest aquaculture production was contributed by mariculture, fish cages, and fishponds. Fishponds, in particular, accounted for the largest area, spanning 85,606 ha or 70.04%, and had the most aquafarms. Mariculture, primar-

Table 2. Top produced aquaculture commodities in terms of volume and value in year 2022

Commodity	Volume ('000 MT)		Value ('000 USD)	
	Amount	% share	Amount	% share
Seaweeds (<i>Kappaphycus</i> & <i>Eucheuma</i> spp.)	1,544.96	65.76	292,120.99	13.39
Milkfish (<i>Chanos chanos</i>)	387.96	16.51	816,574.16	37.42
Tilapia (<i>Oreochromis</i> spp.)	251.83	10.72	377,205.92	17.29
Shrimp/Prawn (<i>Penaeus</i> , <i>Metapenaeus</i> , <i>Macrobrachium</i> spp.)	70.30	2.99	486,268.16	22.29
Shellfishes (<i>Crassostrea</i> , <i>Perna</i> , <i>Modiolus</i> spp.)	50.93	2.17	17,978.29	1.13
Others	43.27	1.84	185,243.29	8.56
Total	2,349.25	100	2,181,677.41	100

Source: PSA⁷; BFAR⁸**Table 3. Major fishery export commodities in terms of shared volume, Free on-board (FOB) value, and major destinations, 2022**

Commodity	Volume (MT)		FOB value ('000 USD)		Foreign destinations
	Amount	% share	Amount	% share	
1. Tuna	106,923	37.8	403,511	33.3	Japan, Germany, USA, Spain, UK of Great Britain and N. Ireland, Netherlands, Italy, Vietnam, Canada, Belgium and others
2. Seaweeds and Carrageenan	48,891	17.3	349,264	28.8	USA, Netherlands, Spain, Germany, China, Mexico, Brazil, India, Australia, UK of Great Britain and N. Ireland, others
3. Crab	9,156	3.2	91,440	7.5	USA, Hong Kong, Taiwan, China, Singapore, Vietnam, Guam, Macau, Thailand, Indonesia and others
4. Eel	22,352	7.9	53,999	4.5	China, Taiwan, Hong Kong, Japan, S. Korea, Vietnam and Australia
5. Octopus	8,372	3.0	51,209	4.2	USA, S. Korea, Japan, Vietnam, China, France, Italy, Dominican Republic, Spain, Canada, and others
6. Grouper	20,572	7.3	37,442	3.1	China, Hong Kong, Taiwan, Singapore, Guam, USA, Macau, Afghanistan, Pacific Trust Territory, Ceuta and Melilla
7. Milkfish	6,661	2.4	36,861	3.0	USA, Canada, Australia, Qatar, UAE, Guam, Thailand, UK of Great Britain and N. Ireland, Netherlands, S. Korea and others
8. Shrimp/Prawn	3,309	1.2	19,743	1.6	Japan, France, USA, S. Korea, Hong Kong, Taiwan, Australia, Vietnam, Guam, Lebanon and others
9. Cuttlefish	4,729	1.7	19,327	1.6	Taiwan, Japan, Hong Kong, S. Korea, Vietnam, China, USA, Thailand, UAE, Guam and others
10. Sardines	7,673	2.7	14,033	1.2	USA, UAE, Canada, Singapore, Hong Kong, Qatar, Australia, Guatemala, Kuwait, Japan and others
Other	43,946	15.6	135,910	11.2	
Total	282,674	100	1.21B	100	

Source: BFAR⁸

ily seaweed farming, ranked next with the most numbered aquafarms and total areas with 30,292 ha or 24.78%. Fish cages followed in third place with 2,849 ha or 2.33%, trailed by fish pens, oyster farms, and mussel farms.

The number of aquafarms is projected to expand in the foreseeable future, driven by the increasing global dependence on aquaculture for aquatic food. In terms of the largest culture areas, fishponds were most prevalent in Regions 3, 6, and 5, covering 19,519, 12,051, and 11,143 ha, respectively. Fish pens were concentrated in Regions 4-A,

11, and 12, with 836, 551, and 293 ha, respectively, while fish cages dominated in Regions 5, 4-A, and 11, with 711, 591, and 544 ha, respectively. Seaweed farming thrived in Regions 7, BARMM, and 9, with culture areas of 13,665, 8,967, and 2,947 ha, respectively. Oyster culture was most prominent in Regions 6, 3, and BARMM, with 365, 34, and 28.5 ha, while mussel farming was led by Regions 4-A, 8, and 5, with 118, 61, and 21 ha, respectively.⁷ This data underscores the regional distribution and importance of various aquaculture systems across the country.

Table 4. Type of culture systems, environments, total number of aquafarms, and total area, 2012

Culture System	Freshwater	Brackish Water	Marine Water	Number of aquafarms	Total Area (ha)
Philippines	61,343	27,395	59,366	148,104	122,223
Fishpond	49,065	21,987	-	71,052	85,606
Fish Pen	1,623	785	694	3,102	2,553
Fish Cage	9,683	2,323	4,347	16,353	2,849
Seaweed Farm	0	0	48,494	48,494	30,292
Oyster Farm	0	1,988	868	2,856	568
Mussel Farm	3	250	787	1,040	233
Fish Tanks	929	57	43	1,029	-
Others	40	5	183	228	122

Source: PSA²⁶

IMPACTS OF AQUACULTURE ON MANGROVE HABITAT

Mangrove forests constitute distinctive coastal ecosystems prevalent in tropical and subtropical zones.^{27,28} These resilient woody seed plants (spermatophytes) thrive in challenging environments characterized by elevated salinity, pronounced tidal fluctuations, powerful winds, high temperatures, and anoxic, muddy substrates.²⁷ As the sole woody halophytes at the land-sea interface, mangroves have historically provided timber, food, medicine and fuel. Spanning approximately 181,000 km² of subtropical and tropical coastlines, mangroves are invaluable economic and ecological assets. Ecologically, they offer shelter and nursery grounds for diverse faunal communities, host biodiversity, serve as carbon sinks, protect coastlines, and filter sediments.²⁹⁻³⁴ Economically, mangroves supply raw materials for wood and serve as vital nurseries for commercially significant fish and marine species, boosting local fishery yields.^{29,35}

Mangroves are distributed across 123 nations and territories, primarily within the tropical and subtropical latitudes of Asia, Africa, and the Americas.³⁰ Within the Philippine archipelago, encompassing 7,641 islands, mangrove forests fringe the coastlines, supporting approximately half of the world's 65 mangrove species.^{27,36,37}

The spatial extent of Philippine mangrove forests has exhibited temporal variations. Initial assessments around 1918 indicated a coverage of approximately 400,000-500,000 ha, but this diminished to roughly 120,000 ha by 1994.³⁶⁻³⁹ Nevertheless, subsequent conservation and restoration initiatives have resulted in a resurgence, with contemporary estimates approximating 311,400 ha.⁴⁰ This substantial reduction in mangrove coverage was principally attributable to overharvesting by coastal populations, expansion of settlements and industries, and conversion to agricultural lands and salt evaporation ponds. However, aquaculture development has been identified as the predominant driver of mangrove deforestation in the Philippines,^{29,36,41,42} especially the cultivation of milkfish (*C. chanos*), wherein it constituted over 95% of brackish-water pond harvest for many years. Historically, fish culture

in brackish mangrove ponds in the Philippines started slowly at 1,200 ha yr⁻¹ in the 1940s and then reached its peak at 5,000 ha yr⁻¹ in the 1950s and 1960s,⁴³ which was spurred by governmental initiatives aimed at bolstering food security and improving the socioeconomic conditions of coastal communities.⁴³⁻⁴⁶ During this period, approximately 237,000 ha of mangrove forests were repurposed for aquaculture, representing nearly 50% of the nation's original mangrove extent.³⁷

Recent estimates in the country indicate a reduced rate of mangrove forest conversion to aquaculture, totaling approximately 522.24 ha between 2000 and 2012.⁴⁶ This is primarily due to government restrictions implemented in the 1970s (PD 705) and in 1982 (PP 2146), which limit and restrict further mangrove conversions to other land uses.⁴³ Additionally, the Department of Environment and Natural Resources (DENR) promulgated Administrative Order No. 3, implementing revised regulations for forestland categorization and zoning to protect mangrove ecosystems.⁴⁷ More recent laws, such as Executive Orders No. 23 and 26, have been enacted to protect remaining mangrove forests and restore denuded areas, promoting their conservation and restoration.⁴⁸

The damage caused by aquaculture expansion to mangrove ecosystems in the Philippines is substantial, not only decreasing mangrove cover but also indirectly degrading vital ecosystem services. Biodiversity, a cornerstone of ecosystem services, contributes to the processes that underpin them, serves as an ecosystem service itself (e.g., genetic resources), and constitutes an ecosystem good directly valued by humans.⁴⁹ As a mega-diverse and biodiversity hotspot,⁵⁰ the Philippines' mangrove biodiversity has been significantly impacted by aquaculture expansion. Six mangrove species have been categorized as Near Threatened (*Aegiceras floridum*, *Ceriops decandra*, *Sonneratia ovata*), Vulnerable (*Avicennia rumphiana*), Endangered (*Camptostemon philippinensis*), and Critically Endangered (*Bruguiera hainesii*) by the IUCN Red List (2024-1). Aquaculture expansion is a primary threat to the continued population decline of these species.⁵¹ These species typically thrive in muddy to sandy substrates in the mid to high intertidal zones (except *A. floridum* and *C. philippinensis*), which are ideal for fishpond development.⁴¹ In Bais Bay,

Bohol, *Ceriops*, *Bruguiera*, and *Xylocarpus* spp., once prevalent in the upper mangrove zones, are now rare or locally extirpated due to aquaculture expansion.⁴¹

Mangroves also provide crucial coastal protection during storm surges, tsunamis, and typhoons. Numerous studies have demonstrated their effectiveness in reducing damage to life and property during such disasters.⁵² In the Philippines, the devastation caused by Typhoon Haiyan in 2013 in Tacloban City, where mangrove forests were converted to aquaculture ponds and settlements, highlights the importance of mangrove protection.⁵³ In contrast, the nearby town of General MacArthur, which also faced the typhoon but maintained its mangrove cover, suffered minimal damage. Residents, administrators, and academics attributed this to the mangroves' ability to dissipate the typhoon's energy and protect the town from the storm surge.⁵⁴ This evidence clearly demonstrates that areas with dense mangrove cover fare better during natural disasters compared to those with converted mangrove forests.

Another critical ecosystem service provided by mangroves degraded by aquaculture conversion is their ability to store carbon. Mangroves are known as net carbon sinks, sequestering substantial quantities of carbon within their biomass and underlying sediments.⁵¹ Notably, their carbon storage capacity per unit area surpasses that of both terrestrial tropical and boreal forests by a factor of three to five,⁵¹ and exceeds that of adjacent seagrass meadows, mudflats, and sandbar ecosystems threefold.^{55,56} However, alterations in land use, particularly the conversion of mangroves to aquaculture, instigate the release of this stored carbon as carbon dioxide (CO₂) and other greenhouse gases (GHGs) through oxidative processes.^{57,58} Furthermore, the introduction of nutrients into aquaculture ponds stimulates the metabolic activity of soil microorganisms, resulting in the emission of additional GHGs, such as nitrous oxide (N₂O) and methane (CH₄).^{58,59} Considering the historical loss of mangrove cover due to aquaculture, the GHGs emitted during this period have likely been significant.

IMPACTS OF AQUACULTURE ON SEAGRASS HABITATS

Seagrasses, unlike seaweed, are marine angiosperms that flourish in estuarine and oceanic settings.⁶⁰⁻⁶⁵ These plants, classified within four families—Cymodoceaceae, Zosteraceae, Posidoniaceae, and Hydrocharitaceae—encompass 60 to 72 species globally.^{64,66-68} Global seagrass coverage estimates vary considerably, ranging from 177,000 to 600,000 km², although a more recent synthesis suggests a total area of 160,387 km², with the potential for expansion to 266,562 km².^{63,69}

The major extensive and diverse seagrass meadows are located in subtropical and tropical countries, especially in the Tropical Indo-Pacific, although large areas remain unexplored.⁶³ These underwater meadows, which grow in shallow coastal waters worldwide except Antarctica, play crucial ecological roles.^{63,64,67} They act as vital nursery grounds for a variety of marine species, capture and store carbon dioxide, stabilize sediments, mitigate erosion, and

protect shorelines.^{63,70} Robust seagrass meadows enhance biodiversity and ecosystem function, supporting resilience against environmental changes.^{71,72} They constitute highly productive and diverse ecosystems that provide habitat and sustenance for marine organisms.^{60,64,67} Occupying roughly 0.1–0.2% of the global ocean surface, seagrasses create vital ecosystems for coastal environments.⁷³

In the Philippines, the diverse seagrass meadows reflect the country's rich marine biodiversity, with approximately 18 species found in significant meadows across the Sulu Sea, Palawan, the Visayas, and Mindanao.⁷⁴ Common species include *Thalassia hemprichii*, *Enhalus acoroides*, *Cymodocea rotundata*, *Syringodium isoetifolium*, and *Halodule uninervis*.⁷⁴ Factors like water depth, salinity, temperature, light availability, sediment type, water quality, and human activities influence seagrass distribution and health in the Philippines.^{60,75,76}

Globally, seagrass ecosystems have experienced a decline of approximately 110 km² annually, primarily due to natural and human disturbances.^{60,66,77,78} Within the Philippines, seagrass habitats encounter substantial pressures from aquaculture, coastal development, pollution, and destructive fishing.^{75,76,79} Built-up areas, residential structures, commercial developments, and roads also significantly impact seagrass meadows.⁸⁰⁻⁸³ Because seagrasses are close to land, they are particularly sensitive to terrestrial activities.⁷³ Areas free from human disturbance often support healthier seagrasses, while watersheds, expanded farmlands, and increased development are typically detrimental.⁸⁴

The expanding aquaculture industry also poses risks to seagrass ecosystems, particularly through fish pens and cages.^{14,60} Global seagrass losses have placed these ecosystems among the most threatened, largely due to eutrophication and the subsequent degradation of underwater light conditions.⁸⁵ The impacts of aquaculture on seagrasses are complex and can be both harmful and beneficial, though negative impacts generally predominate.^{81,86} Annual seagrass loss rates due to anthropogenic disturbances is ranging from 1% to 2% per year globally, but the specific role of aquaculture in this remains unclear, highlighting the need for data-driven policies to address habitat destruction from aquaculture development and expansion.^{87,88}

Aquaculture practices can damage seagrass meadows through fish cage installations, dredging, and increased boat traffic, which cause disturbance, uprooting, sedimentation, and reduced light availability for photosynthesis. Nutrient-rich aquaculture effluents also promote eutrophication, leading to massive algae production that smother seagrass.⁸⁹ In some cases, however, aquaculture practices are managed to protect or even benefit seagrass habitats, such as bivalve aquaculture, which improves water clarity by filtering particles, thus supporting seagrass growth.⁹⁰ Integrated multi-trophic aquaculture systems can also sustain seagrass health by reducing nutrient loads and minimizing disruptions.⁸⁵ However, when poorly managed or located without regard for seagrass meadows, aquaculture often proves more harmful than beneficial.

Seaweed farming, a prominent aquaculture activity in the Philippines,^{6,91-94} likely also threaten seagrass habitats. Large seaweed farms, particularly in the southern Philippines where *E. acoroides* and *T. hemprichii* are common,⁹² frequently removing seagrass beds, lowering primary productivity and reducing marine habitats.^{68,95,96} Traditional or manual seaweed harvesting methods, such as hand-cutting, bottom trawling, especially the occasional stepping of the harvesters to the seabed, were proven to further endanger seagrass by damaging shoots and leaves.^{71,97,98} While less frequent, uprooting during harvesting also disrupts seagrass meadows.^{99,100}

Seagrass loss due to seaweed farming disrupts biodiversity, food webs, sediment stabilization, and water clarity, hindering the growth of remaining seagrasses.¹⁰¹⁻¹⁰³ Boats used in seaweed farming can physically damage seagrasses through propeller scarring and sediment disturbance.^{60,96,104} A recent study in Tawi-Tawi, southern Philippines, found lower seagrass cover in areas with active seaweed farming, indicating its adverse effects on these habitats.¹⁰⁵ Additionally, sedimentation and nutrient discharge from seaweed farming community houses pose threats, as sediment deposits on leaves and nutrient-driven algal blooms can further degrade seagrass.¹⁰⁶⁻¹⁰⁹

CHEMICAL POLLUTION AND WATER QUALITY DEGRADATION CAUSED BY AQUACULTURE

Technological advancements and cultural practices have significantly influenced the expansion of Philippine aquaculture production.^{8,25} The pursuit of higher productivity has fostered the widespread application of intensive labor and advanced technologies, resulting in high-input systems with increasing stocking densities.^{9,10} While extensive aquaculture has made substantial contributions to the global food supply, it also has environmental drawbacks, including water quality degradation due to chemical pollution.

NUTRIENT-RICH AND ORGANIC MATTER-LADEN EFFLUENTS

Nutrient and organic matter accumulation in aquatic environments is a common issue in nearly all aquaculture regimes, from intensive freshwater fishponds and brackish-water ponds to marine facilities.^{6,110-112} These methods, particularly those involving high stocking densities, generate effluents high in nutrients like carbon, phosphorous, and nitrogen.^{113,114} This effluent can lead to water quality deterioration, eutrophication, and algal blooms, which deplete dissolved oxygen and reduce water clarity.^{25,115,116} Aquaculture effluent can also carry high levels of nutrients that support phytoplankton growth and further degrade water quality.^{111,116} Additionally, factors like increasing water temperature and the disposal of saltwater wastewaters into brackish water ecosystems can exacerbate these environmental impacts in areas such as Luzon and Mindanao in the Philippines.^{6,112}

TOTAL DISSOLVED SOLIDS (TDS), TOTAL SOLIDS (TS), AND TOTAL SUSPENDED SOLIDS (TSS)

Freshwater aquaculture installations can affect the levels of TDS and TS, particularly during fish removal. The usual concentration of TDS (22.5 – 76.25 mg L⁻¹) in cage locations is higher compared to places without aquaculture owing to the accumulation of inorganic and organic elements from feed and waste materials.^{6,111} High levels of TSS can also physiologically disturb fish.^{114,117} In Lianga Bay, Surigao del Sur, Philippines, fish cages (milkfish and jackfish) dramatically increase water's TSS to over 52 mg L⁻¹, compared to under 30 mg/L⁻¹ in areas without cages, indicating aquaculture's significant impact on water clarity.¹¹⁸

OXYGEN DEMAND

Intensive aquaculture can alter nutrient cycling, leading to a decline in oxygen levels in the water body, which can impact biodiversity and ecosystem health. While organic wastes from fish excreta and unconsumed feed can initially increase dissolved oxygen (DO) and reduce biochemical oxygen demand, they can also contribute to long-term oxygen depletion. The surprisingly high levels of chemical oxygen demand during fish extraction indicate that organic substances increase the oxygen demand. During oxygen dissolution at aquaculture facilities, especially in high stages of production, DO levels can decline, leading to fish mortalities and ecosystem deterioration. This can lower DO levels, allowing algal blooms to become more frequent and organic matter decomposition to accelerate, resulting in severe environmental impacts.^{114,117}

In Lake Buhi, Philippines, fish kills in lake cage aquaculture occur and reoccur annually, largely due to unsustainable farming practices. Overstocking and overfeeding create excessive organic waste, depleting DO and elevating harmful by-products like ammonia and hydrogen sulfide. These conditions, compounded by natural stressors such as typhoons and temperature changes, establish recurring lethal environments for farmed fish.¹¹⁹

In Bolinao, Philippines, a major fish kill in 2002, coinciding with a *Prorocentrum minimum* bloom, was primarily caused by severe oxygen depletion. DO levels plummeted below 2.0 mg/L⁻¹ in stratified waters, a direct result of excessive organic matter from overstocked fish pens and cages, exceeding the allowable limit. This uncontrolled aquaculture proliferation, coupled with poor water circulation, led to eutrophication and significantly degraded water quality over a decade, culminating in the oxygen-deprived conditions that triggered the fish kill.¹²⁰

A significant fish kill, affecting both fin fish and crustaceans, occurred in the Ilog River-Estuary in Negros Occidental, Philippines, from April 22-26, 2013. The primary cause was identified as severe hypoxia, with DO levels plummeting to a range of 0.6-3.86 mg L⁻¹ during the event's onset.¹²¹

PHOSPHORUS CONTAMINATION

Phosphorus is an essential nutrient for aquatic life, but excess phosphorus can cause oxygen depletion, harmful algal blooms, and eutrophication problems in water bodies.¹²²⁻¹²⁴ Aquatic environmental phosphorus levels are generally higher in areas with intensive aquaculture compared to areas without aquaculture activities^{6,117,125} due to the accumulation and decomposition of uneaten feeds. An estimated 0.5 million tons of phosphorus are added to the system yearly due to these intensive aquaculture operations.¹²⁶ Manila Bay, located in the western part of Luzon and home to about 39 km² of fish cages, contributes 2,363.01 MT of phosphorus annually to the Philippines, with 14% originating from fishponds and 86% from fish pens and cages.^{115,117} Phosphorus levels vary seasonally, characterized by elevated levels during the dry season and diminished levels during the wet season. The content of phosphate in Manila Bay ranges between 1.02 and 2.42 mg L⁻¹, which is higher than what is acceptable for fish aquaculture.⁶ In Bolinao, Pangasinan, another notable aquaculture center in the Philippines, the projected annual phosphorus discharge is almost 400 kg km⁻², far exceeding the global average of 230 kg km⁻² for areas with intense aquaculture. This suggests that areas with phosphorus inputs greater than 130 kg km⁻² per year are more likely to experience toxic algal blooms.¹¹⁵ Agricultural runoff due to rainfall can further exacerbate phosphorus pollution.¹¹¹

Recently, phosphorus input in many aquaculture areas has increased, surpassing critical thresholds that result in negative environmental effects like eutrophication and hypoxia.^{115,127-130} Remaining feed, wastes, and metabolic by-products are significant contributors to phosphorus pollution, as they can lead to toxic algal blooms, especially those due to cyanobacteria, posing threats to ecosystems, public health, and marine organisms.^{123,124,131,132} In Manila Bay, leftover feed from fish pens and cages contributes significantly to phosphorus pollution.¹¹⁷ Poor pond preparation can also be a contributing factor in areas like Eastern Bulacan.¹¹⁴ Intensive fish cage farming can worsen eutrophication by contributing to the buildup of phosphorus in sediments, turning them into phosphorus reservoirs.^{111,115} Due to intensive fish cage configurations and nutrient inputs, the annual phosphorus loading in some aquaculture areas can exceed 200 kg km⁻² per year, far greater than their natural state.^{6,133} These outflows, primarily from fish wastes and feeds, can significantly increase phosphorus levels, leading to a higher risk of eutrophication and oxygen depletion in the affected water bodies.

NITROGEN CONTAMINATION

Intensive aquaculture can significantly increase nitrogen levels in the environment.^{6,117,125} Aquaculture facilities are estimated to release approximately 2.7 million tons of nitrogen into the natural environment annually.¹²⁶ In the Philippines, phosphorus pollution often coincides with elevated nitrogen levels in freshwater systems due to effluent discharges from aquaculture activities, leading to eutrophication and water quality deterioration.^{117,134} Manila Bay

alone receives over a thousand MT of nitrogen annually, with 88% attributed to fish pens and cages.^{115,117}

Aquaculture systems, particularly freshwater facilities with intensive fish cages, release ammonia and nitrates (species of nitrogen) originating from fish waste and residual feed, contributing to the nutrient burden.^{110,111} Excessive ammonia can hinder fish development, cause tissue damage, reduce growth, and increase susceptibility to diseases.^{114,135,136} Flooding can increase ammonia levels due to organic contamination upstream.¹¹⁶ The production of nitrite and nitrate in pond drainage indicates nitrification, which can adversely affect fish, such as causing brown blood disease.^{110,117} The decomposition process yields nitrogen compounds dominated by ammonia and total Kjeldahl nitrogen (TKN), which can reach exceptionally high levels during flooding and drainage. Ammonia levels have been recorded between 0.79 and 4.63 mg L⁻¹, while TKN concentration ranges from 1.56 to 6.76 mg L⁻¹.¹¹⁶ Ammonia levels exceeding 0.90 to 2.35 mg L⁻¹ are unfavorable for fish cultivation.⁶

Intensive aquaculture contributes significantly to nutrient loading, particularly nitrate-nitrogen, emphasizing the need for sustainable practices to reduce environmental effects.^{116,117} The use of inorganic fertilizers, such as ammonium phosphate (16-20-0) and complete (14-14-14) fertilizers, in eucheumatoid seaweed aquaculture in the southern Philippines raises concerns about their potential impacts on the marine environment.^{91-93,137} Farmers often dispose of the bulk nutrient solution, containing nitrogen and phosphorus, into the sea after using it for seaweeds. The high nutrient levels in the marine environment can have detrimental effects, such as the proliferation of green macroalgae like *Ulva* and *Chaetomorpha* spp.^{91,94,137,138} as well as harmful algal blooms.

SEDIMENT NUTRIENT ACCUMULATION

Aquaculture practices can significantly impact nutrient accumulation in sediments, with variations between farm types and environments. Aquaculture facilities can increase the risk of phytoplankton blooms, inhibit dissolved inorganic nitrogen flux, and prolong nutrient residence time, all contributing to sediment nutrient accumulation.¹³⁹ However, co-culture systems with rice, catfish, and shrimp have demonstrated greater success in controlling nutrient fluxes compared to monoculture systems, with lower ammonium levels and more stable sediments.¹⁴⁰

The expansion of aquaculture can lead to increased sediment nutrient accumulation, particularly phosphorus enrichment in areas with high cage concentrations. Excessive phosphorus absorption can degrade water quality and affect the development of phytoplankton and submerged aquatic vegetation.^{113,115} Also, benthic sediments around fish farms are often highly enriched in phosphorus, significantly enhancing the benthic phosphorus flux and contributing to eutrophication and nutrient cycling in coastal ecosystems.¹³¹

HEAVY METALS

Research on heavy metals in aquaculture in the Philippines is limited. However, heavy metals in these operations often originate from industrial activities, agricultural runoff, contaminated fish feed, and chemical additives, as well as sediment accumulation. Once introduced to the ecosystem, these metals infiltrate feed and sediment, presenting potential hazards to human and aquatic health via bioaccumulation within the food web. To safeguard marine environments and public health, effective remediation and monitoring measures are essential.¹⁴¹⁻¹⁴⁵

In Lingayen Gulf, a study on shellfish revealed cadmium levels in oysters that surpassed acceptable limits, raising public health concerns.¹⁴⁶ Likewise, Solidum et al.¹⁴⁷ found lead, cadmium, and chromium in milkfish and tilapia sold in Metro Manila, with two of these metals exceeding safe thresholds. Albarico & Pador¹⁴⁸ also detected cadmium in organic milkfish farms in Negros Occidental. Consuming seafood with these metals above permissible levels can lead to organ damage in humans.¹⁴⁹

Heavy metals pose a significant threat to human health in aquaculture, primarily owing to their tendency to accumulate in sediment from contaminated feed and water sources, which facilitates their entry into the food chain. Research has detected various heavy metals in aquaculture environments, including Cd, Cr, Pb, Ni, Co, As, Zn, Mn, Hg, and Cu.^{141,143-145} Among these, Pb, Hg, and Cd are particularly hazardous. Lead's presence in aquaculture sediments is especially concerning due to its severe neurological and developmental impacts, particularly in children.^{141, 144} Mercury is also alarming for its high toxicity, bioaccumulation, and elevated target hazard quotient, posing risks to aquatic life and human health.^{141,144} Cadmium, even within regulatory limits, remains a concern for its carcinogenic and toxic effects.^{144,145}

TOXIC CHEMICALS

Extensive aquaculture practices introduce several toxins into aquatic environments, each with unique risks to both ecosystems and human health. Oxytetracycline, an antibiotic produced by *Streptomyces rimosus*, is commonly used in aquaculture. However, due to its low metabolic assimilation in fish, oxytetracycline persists in aquatic environments, where it can form toxic metabolites. This persistence not only harms aquatic ecosystems but also contributes to the development of antibiotic-resistant bacteria, posing additional risks to public health.^{150,151}

Sulfate-reducing bacteria in marine recirculating systems produce hydrogen sulfide—a toxic compound—through anaerobic metabolism. Factors such as sulfur levels in feed and high salinity in sludge promote hydrogen sulfide production, with concentrations reaching harmful levels (1803–2074 ppm). This compound adversely affects fish by inducing hypoxia and impairing mitochondrial ATP synthesis, which is crucial for energy production. Hydrogen sulfide also disrupts microbial populations, affecting nutrient cycling and degrading water quality. Fur-

thermore, its corrosive effects increase aquaculture operational costs due to equipment deterioration.¹⁵²⁻¹⁵⁴

Mycotoxins, produced by fungal species like *Aspergillus* and *Fusarium*, represent another hazard in aquaculture. These fungi can contaminate fish feeds, introducing toxins such as aflatoxins, fumonisins, and ochratoxin A. Such contaminants impair fish growth, weaken immune responses, and damage cellular structures like lysosomes, mitochondria, and plasma membranes. Infected feed not only threatens fish health but also poses immunosuppressive and carcinogenic risks to animals and humans via food web. The increased use of plant-derived ingredients in aquafeeds heightens the risk of mycotoxin contamination, underscoring the need for stringent monitoring protocols to maintain food safety.^{155,156}

DETERIORATION OF SEDIMENTS (SUBSTRATES) DUE TO AQUACULTURE

Aquaculture, while providing valuable sources of food and economic benefits, can also pose significant environmental challenges, like sediment deterioration, particularly when fish pens and cages are used. Fortes¹⁵⁷ highlighted that these structures have substantial and varied impacts on aquatic ecosystems, with substrate quality playing a crucial role. Open-net pen systems, commonly employed in aquaculture, allow waste, pollutants, and uneaten food to move freely between the farm environment and surrounding natural waterways. This exchange results in nutrient enrichment, pollution, and notable changes in sediment composition and quality, ultimately affecting benthic ecology. Similar findings by Moncada et al.¹⁵⁸ in Bolinao, Philippines, demonstrated that intensive mariculture operations caused organic enrichment of sediments. Organic carbon levels were significantly higher in mariculture sites compared to control areas, as uneaten feed, fish waste, and other organic materials settled on the seabed, increasing the organic matter content. This enrichment fosters eutrophic conditions, where highly concentrated nutrients stimulate the proliferation of algae and microorganisms. Subsequently, this environment becomes anoxic, which may cause fish to die.

In Bolinao-Anda, Philippines, intensive fish farming has led to severe oxygen depletion and the prevalence of sulphidic conditions in the sediments, rendering them inhospitable for most macrobenthic organisms.¹⁵⁹ Excessive fish feed deposition can also counteract the beneficial effects of macrofauna, increasing hydrogen sulphide production and reducing the survival of sensitive species.¹⁵⁹ Additionally, milkfish farming in Bolinao has a serious effect on bacterial communities in the underlying sediments. The area within fish cages exhibited anoxic conditions, characterized by lower redox potential and elevated levels of acid-volatile sulfide-sulfur, creating an environment favorable for sulphate-reducing bacteria. These bacteria dominated the microbial populations within the cages, while the off-cage area maintained relatively toxic conditions with a less diverse bacterial community. Organic matter from fish feed

and its residual components played a key role in shaping the bacterial structure in milkfish farms.¹⁶⁰

Further research into aquaculture feeds explored the environmental impacts of plant proteins. Microcosm experiments comparing various feed types (fishmeal only, soybean-copra-fishmeal, and soybean-wheat-fishmeal) and feed levels (low and high) revealed that all feed treatments created toxic and anoxic conditions, with higher ammonium-N concentrations in plant-protein feeds. Protein concentrations in sediments were highest with soybean-wheat-fishmeal feed, and both low and high feed levels resulted in poor sediment quality. These findings suggest that plant proteins may have detrimental effects on sediment quality, similar to traditional fishmeal-based feeds.¹⁶¹

ANTIBIOTIC-RESISTANT GENES AND RESIDUES IN CULTURED ORGANISMS IN AQUACULTURE

Antibiotics are medications that combat bacterial infection by inhibiting or killing their growth and reproduction. They are widely employed in treating infections across humans, terrestrial animals, and aquaculture.¹⁶² In intensive aquaculture, antibiotics are applied to prevent disease and to enhance fish health and growth, ultimately maximizing production.¹⁶²⁻¹⁶⁶ The antimicrobials most frequently employed in the Philippine aquaculture include quinolones, tetracyclines (oxytetracycline), amphenicols, sulfonamides (sulfadiazine), and florfenicol.^{164,167}

The global demand and consumption of aquatic food have driven a significant increase in antibiotic use in aquaculture. Between 2000 and 2018, the projected global antibiotic consumption rate rose by 46%, from 9.8 defined daily dose (DDD) per 1000 per day to 14.3 DDD per 1000 population per day.¹⁶⁸ The aquaculture industry's global antimicrobial consumption is projected to skyrocket by 33% from 10,259 tons in 2017 to 13,600 tons in 2030.¹⁶⁷ When combined with consumption in human, terrestrial, and other aquatic animal food-producing sectors, the total annual antimicrobial consumption is expected to be 236,757 tons by 2030.¹⁶⁷

Despite the Philippines' prominent role as a major global producer of aquatic products,⁴ it is also ranked sixth in a survey of the top-10 countries with the most studies on antibiotic resistance.^{166,169} The major antibiotics used in the Philippines are chloramphenicol, ampicillin, tetracycline, and erythromycin, which are used against Motile *Aeromonas Septicemia*, *Streptococcus*, and *Pseudomonas* infections caused by *Aeromonas hydrophila*, *Streptococcus iniae*, *S. agalactiae*, *Pseudomonas aeruginosa*, and *P. fluorescens*, respectively.¹⁷⁰ Other antibiotic residues such as oxolinic acid and oxytetracycline have been found in samples of tilapia, milkfish, sea bass, grouper, snapper, silver perch, rabbitfish, catfish, carp, white shrimp, freshwater prawn, and tiger shrimp in the Philippines to treat against infectious bacteria such as *Flavobacterium columnare*, *Aeromonas* sp., *Mycoplasma pneumonia*, *Haemophilus influenza* and *Escherichia coli*.¹⁷¹

The excessive and long-term utilization of antibiotics in aquaculture can lead to the development of antibiotic-re-

sistant genes in bacteria and the accumulation of antibiotic residues in aquatic animals or in aquatic systems.¹⁷² Aquaculture-farmed organisms have been reported to contain antibiotic-resistant *Aeromonas* spp. in Danish fish farms,¹⁷³ *E. coli* in Chilean salmon,¹⁷⁴ *Enterococcus* in Nile Tilapia in Egypt,¹⁷⁵ and *Streptococcus* in Nile Tilapia in the Philippines.¹⁷⁶

Several studies in the Philippines have reported that the application of antibiotics in aquaculture is common,¹⁷⁰ and antimicrobial resistance in aquaculture has been observed.^{17,176} Other significant and far-reaching consequences include impacts on human health,¹⁷⁷ the environment,¹⁷⁸ and the aquaculture industry itself.

The prolonged use of antibiotics in aquaculture can promote the development of antibiotic-resistant bacteria.¹⁷⁹ These bacteria can transfer resistance genes to human pathogens, making infections more challenging to treat and reducing the effectiveness of antibiotics. Depending on the antibiotic type and concentration, humans consuming aquaculture products with antibiotic residues may face health risks,¹⁷⁵ including allergic reactions and toxicity, disruption of gut microbiota, and the emergence of antibiotic-resistant bacteria.^{180,181} Excessive use may also cause occupational health hazards and food safety issues.¹⁶⁶

Over 70% of the antimicrobials added to feed in intensive fish farming operations seep into the environment.^{182, 183} Antibiotics released into water bodies can accumulate antibiotic residues, aquatic biodiversity toxicity, natural microbial imbalance, and the emergence of multi-antibacterial strains.^{164,166} Residues in water and sediment can contribute to the development and spread of antibiotic-resistant bacteria in aquatic environments,¹⁷⁷ which can then be transferred to other animals and potentially back to humans.¹⁶⁶ The enduring nature of certain antibiotics allows for their concentration within the tissues of aquatic biota, potentially propagating adverse effects across higher trophic levels and jeopardizing the well-being of the entire ecosystem. Concurrently, the selective pressures exerted by these compounds frequently facilitate the proliferation of bacteria exhibiting antibiotic resistance, along with the dissemination of resistance genes throughout aquatic environments.¹⁸⁴

Antimicrobial resistance (AMR) genes in aquaculture are a growing concern due to their potential to spread resistance to pathogens affecting both aquatic and terrestrial life, including humans.¹⁸⁵ The primary driver of AMR in aquaculture is the use of antibiotics to prevent and treat infections.¹⁷⁷ The injudicious or inappropriate application of antimicrobials can foster the selection of resistant bacterial strains, creating the potential for horizontal gene transfer of resistance determinants from aquaculture-associated bacteria to human pathogens.¹⁷⁵ These resistant bacteria can disseminate AMR genes to other bacteria via mechanisms like transformation, conjugation, and transduction,¹⁶⁶ potentially leading to the conjugation of these genes with human pathogenic strains.¹⁶³ This can occur within the aquatic environment, including in sediments and water.

Antibiotic residues in aquaculture are a significant concern owing to their potential effect on human health and the environment.¹⁶⁶ Excessive or inappropriate use of antibiotics can lead to residues remaining in the tissues of aquatic animals and may account for advanced patterns of antimicrobial resistance in clinical pathogens and adverse drug reactions.^{186,187} Antimicrobial residues such as tetracycline, florfenicol, ceftiofur, streptomycin, quinolone, and tylosin were investigated in lateral muscle tissue samples collected from Nile tilapia (*Oreochromis niloticus*) in Laguna, Philippines.¹⁸⁸

Antibiotic residues and resistant bacteria can enter aquatic environments through wastewater, agricultural runoff, and direct discharge from aquaculture operations.¹⁶⁶ AMR genes are easily spread. Once in the water, AMR genes can be taken up by various microorganisms, spreading resistance within the ecosystem.¹⁶³ The consumption of resistant bacteria by aquatic organisms can facilitate their trophic transfer, potentially culminating in human exposure through the consumption of contaminated seafood.^{189,190} Fishermen, aquaculture workers, and others in contact with contaminated water can become carriers of resistant bacteria, facilitating the spread of AMR genes.¹⁹¹

Growing evidence of antibiotic residues in aquaculture products may result in more stringent export laws and prohibitions, affecting aquaculture companies' ability to access markets and make a profit. Implementing measures to monitor and reduce antibiotic use can increase operational costs for aquaculture farms.¹⁶⁴ Additionally, the need to manage antibiotic-resistant infections can lead to higher expenses for alternative treatments and preventive measures. Negative public perception and consumer distrust of aquaculture products due to concerns about antibiotic residues can reduce demand and harm the industry's reputation.

Sustained investigation into the effects of antibiotics, coupled with the creation of novel and ecologically sound disease management strategies, is essential for mitigating long-term risks.^{166,175} Effectively addressing these challenges necessitates a collaborative approach involving regulators, industry stakeholders, and researchers to guarantee the implementation of sustainable and safe aquaculture practices.¹⁶⁴ Implementing best practices in aquaculture management can reduce the need for antibiotics and antibiotic residues, such as improving water quality, and using non-antibiotic treatments such as probiotics, prebiotics, and phyto-based products¹⁹² to manage diseases.

Therefore, the dissemination of AMR genes within aquaculture systems presents a substantial threat to public health, as it can lead to human infections that are refractory to conventional antibiotic therapies. Resistant pathogens can affect the health of farmed fish and shellfish, leading to increased disease outbreaks and mortality rates.^{193,194} The presence of AMR genes can alter microbial communities and ecological balances, impacting overall biodiversity and ecosystem functions. Strategies to mitigate AMR include implementing strict guidelines and best practices for antibiotic use can help minimize the selection pressure for resistant bacteria.¹⁶²

EFFECTS OF AQUACULTURE ON BIODIVERSITY

Aquaculture has emerged as a significant global food production system. While it offers potential benefits like reduced pressure on wild stocks and job creation, it also poses risks to biodiversity. This section explores the negative and positive consequences of aquaculture on biodiversity, drawing on existing research and case studies in the Philippines.

POSITIVE IMPACTS ON BIODIVERSITY

REDUCED PRESSURE ON WILD STOCKS

Aquaculture plays a crucial role in alleviating pressure on overexploited wild populations, contributing to marine and freshwater ecosystem conservation. Research has shown that the aquaculture of specific fish species can reduce fishing pressure on their wild counterparts, aiding in population recovery.¹⁹⁵ In the Philippines, the shift toward hatchery-bred fry in milkfish (*C. chanos*) farming has significantly reduced dependence on wild-caught juveniles, helping replenish natural stocks.¹⁹⁶ Similarly, the cage culture of high-value species such as groupers (*Epinephelus* spp.) in Mindanao and tilapia (*O. niloticus*) in Laguna de Bay has provided alternative livelihoods while reducing fishing pressure on wild populations.^{197,198} Beyond finfish, wildlife farming has emerged as an essential conservation tool. Seahorse (*Hippocampus* spp.) aquaculture supports the aquarium and traditional medicine trade, reducing wild capture, though challenges such as low larval survival persist.^{199,200} Sea cucumber (*Holothuria scabra*) ranching in the Philippines and Madagascar has replenished wild stocks while sustaining coastal communities.^{201,202} Additionally, giant clam (*Tridacna* spp.) farming in Palau and the Philippines has aided reef restoration and mitigated pressure from the ornamental trade.^{203,204} Abalone (*Haliotis* spp.) aquaculture in South Africa and China has provided a sustainable seafood alternative, reducing overfishing.^{205,206} Coral farming, particularly with *Acropora* spp., supports global reef restoration efforts.^{207,208} These initiatives highlight the critical role of responsible aquaculture in biodiversity conservation and fisheries management. However, ensuring its long-term sustainability requires stringent regulatory enforcement, habitat protection, and genetic diversity preservation to prevent unintended ecological consequence.^{209,210}

ENHANCING DEPLETED STOCKS

Finfish aquaculture plays a vital role in replenishing depleted fish stocks and supporting sustainable fisheries management. By providing an alternative source of commercially valuable species, aquaculture alleviates fishing pressure on wild populations while facilitating restocking programs. This approach has been widely implemented in the Philippines and globally to aid in population recovery and enhance fishery productivity.²¹¹ In the Philippines, the Philippine National Aquasilviculture Program (PNAP) was launched in 2012 as a joint initiative between the Bureau of Fisheries and Aquatic Resources (BFAR) and the Commis-

sion on Higher Education (CHED) to improve fisheries productivity and aquatic resource management through aquasilviculture.²¹² BFAR has also actively promoted the release of hatchery-bred juveniles into coastal and brackish-water environments to support population recovery. Notably, the restocking of Asian sea bass (*Lates calcarifer*) in mangrove-protected estuaries has successfully replenished natural stocks and bolstered small-scale fisheries.¹⁹⁶ Similarly, the introduction of hatchery-reared Nile tilapia (*O. niloticus*) in Laguna de Bay has significantly enhanced fish production and improved local food security.²¹³

The impact of restocking initiatives extends beyond the Philippines. Internationally, stock enhancement programs have contributed to the recovery of commercially valuable species such as Atlantic cod (*Gadus morhua*) in Norway and Atlantic salmon (*Salmo salar*) in Canada.^{214,215} Likewise, advancements in hatchery technologies for Pacific bluefin tuna (*Thunnus orientalis*) in Japan and yellowtail amberjack (*Seriola quinqueradiata*) in Australia have provided sustainable alternatives to wild capture, helping stabilize stock levels and mitigate overexploitation.^{216,217} In the Philippines, hatchery production of groupers (*Epinephelus* spp.) has supported both mariculture and restocking programs, benefiting fisheries while aiding coral reef ecosystem restoration.²¹⁸ These efforts underscore the critical role of aquaculture in restoring depleted stocks and ensuring long-term fisheries sustainability. However, for stock enhancement programs to be effective, factors such as proper site selection, genetic monitoring, and habitat conservation must be prioritized to maintain biodiversity and ecological balance.²¹⁹

BOOSTING NATURAL PRODUCTION

Aquaculture operations can contribute to local biodiversity and ecosystem productivity by enhancing nutrient cycling and promoting the recovery of fish populations. Effluents from aquaculture facilities, particularly those with integrated multi-trophic aquaculture (IMTA) systems, can introduce nutrients into surrounding waters, stimulating the growth of phytoplankton and aquatic vegetation, which serve as food sources for various fish and invertebrates.²²⁰ This nutrient enrichment can indirectly support the recovery of native fish populations and increase overall fisheries productivity. In the Philippines, the BFAR-National Inland Fisheries Technology Center has implemented the National Program on the Fisheries Enhancement of Inland Waters, known as “Balik Sigla sa Ilog at Lawa” (BASIL). This program aims to restore indigenous fish populations, improve aquatic biodiversity, and maximize the natural productivity of rivers, lakes, reservoirs, and dams.²²¹ The initiative has successfully restocked native species such as Aruan (*Lates calcarifer*), Ayungin (*Leiopotherapon plumbeus*), and Martiniko (*Anabas testudineus*) in major inland water bodies like Laguna de Bay, Lake Lanao, and the Agusan Marsh, Philippines, where populations had previously declined due to overfishing and habitat degradation. As a result, local fisheries have reported increased catch volumes, demonstrating the program’s effectiveness in revitalizing fish stocks and supporting sustainable livelihoods.⁸ Finfish

aquaculture also enhances local biodiversity and ecosystem productivity by improving nutrient cycling and supporting fish population recovery. In Bolinao, Philippines, *C. chanos* (milkfish) aquaculture has increased nutrient fluxes, stimulating benthic processes and primary production.²²² Similarly, in Laguna de Bay, aquaculture sites have shown higher finfish biomass and improved nutrient utilization, fostering diverse fish communities.²²³ Internationally, IMTA in Canada integrates *Salmo salar* (Atlantic salmon), *Mytilus edulis* (blue mussel), and *Saccharina latissima* (kelp) to optimize nutrient recycling and minimize environmental impacts. Meanwhile, China’s polyculture systems efficiently utilize resources, promoting biodiversity and ecosystem productivity.²²⁴ These initiatives underscore aquaculture’s critical role in sustainable fisheries management, but proper site selection, genetic monitoring, and habitat conservation remain essential to mitigate ecological risks.²²⁴

NEGATIVE IMPACTS OF AQUACULTURE

INTRODUCTION OF INVASIVE SPECIES

Aquaculture escapees’ organisms can become invasive disrupting native ecosystems and outcompeting native species.^{225,226} For example, the introduction of non-native fish species through aquaculture has led to significant ecological damage in various regions.²²⁷ In the Philippines, four fish species introduced for aquaculture have become invasive: *Clarias batrachus*, *C. striata*, *O. mossambicus*, and *Monopterus albus*. *C. striata*, the mudfish, exhibits predatory behavior towards juvenile cultured fish when migrating from natural habitats into freshwater ponds.²²⁸ *C. batrachus*, the Asiatic catfish, has supplanted the indigenous catfish, *C. macrocephalus*, within Laguna de Bay.²²⁹ *M. albus*, the rice paddy eel, preys upon small fish and shrimp inhabiting rice paddies.^{230,231} *O. mossambicus*, the Mozambique tilapia, has established itself within brackishwater ponds utilized for milkfish aquaculture.²²⁹ The extirpation of 15 of the 18 endemic cyprinid species in Lake Lanao (Lanao del Sur) has been attributed to the inadvertent introduction of the white goby, *Glossogobius giuris*, and the eleotrid, *Hypseleotris agilis*, originating from Lake Mainit (Surigao) in Mindanao.²³²

POLLUTION THAT AFFECTS BIODIVERSITY

Aquaculture operations can generate pollutants such as excess nutrients, antibiotics, and organic waste that can degrade water quality and harm aquatic ecosystems, leading to eutrophication that encourages harmful algal blooms and reduced biodiversity.²³³ In Taal Lake, Philippines, aquaculture cages have significantly contributed to water quality degradation. High concentrations of total dissolved solids, phosphates, and nitrates, have been detected in areas with aquaculture cages.¹¹⁴ Additionally, DO levels and water transparency near aquaculture cages have been consistently lower, with critical low DO levels observed during January and February.¹²⁵ Furthermore, high dissolved inorganic phosphorus concentrations, indicating eutrophica-

tion, have been reported in Bolinao and Anda waters.²³⁴ These poor water quality conditions have detrimental effects on aquatic biodiversity.

HABITAT DESTRUCTION IMPAIRING BIODIVERSITY

The expansion of finfish aquaculture can lead to the destruction of ecologically critical habitats such as mangroves, seagrass beds, and coral reefs, resulting in significant biodiversity loss and ecosystem service disruption.²³⁵ The Philippines has witnessed a sharp decline in mangrove cover due to aquaculture expansion, reducing nursery habitats for commercially valuable species like *Chanos chanos* (milkfish) and *Penaeus monodon* (black tiger shrimp).¹⁴ The degradation of these ecosystems directly affects fishery yields, as mangroves serve as spawning and nursery grounds for a wide range of marine species.²³⁶ The loss of critical habitats has profound cascading effects on aquatic biodiversity, leading to declines in fish and crustacean populations, lower recruitment rates, and reduced fishery productivity. The widespread conversion of mangrove forests for shrimp farming has significantly impacted coastal ecosystems, as these habitats serve as crucial nurseries for various marine species.²³⁷ In the Philippines, the removal of mangrove buffers has increased sedimentation in coastal waters, accelerating the decline of seagrass meadows, which are essential for juvenile fish and invertebrates.²³⁸

Several case studies illustrate the consequences of habitat destruction. In Lingayen Gulf, large-scale aquaculture development has replaced extensive mangrove areas, reducing fish nursery habitats and leading to a decline in local fish stocks.²³⁹ Similarly, in Thailand, intensive shrimp aquaculture has resulted in the loss of mangroves, biodiversity decline, and long-term productivity reduction due to soil acidification and pollution.²⁴⁰ Indonesia has also experienced severe coastal degradation from excessive brackish-water pond development, which has destroyed natural coastal buffers, increased erosion, and diminished fishery yields.²⁹ In Bolinao, Philippines, nutrient pollution from fish cages has led to the collapse of seagrass meadows, reducing habitat availability for herbivorous fish and disrupting the local food web.²⁴¹ These examples highlight the urgent need for sustainable aquaculture practices and habitat conservation measures to mitigate the negative impacts of aquaculture-driven habitat loss.

OVEREXPLOITATION OF RESOURCES

Aquaculture often relies on fishmeal and fish oil as feed ingredients, contributing to the overexploitation of wild fish stocks. This can create a negative feedback loop, as the demand for aquaculture products increases the pressure on wild fish populations.²⁴²

Global marine fisheries data reveal that 40% of the total annual catch, amounting to 63 billion pounds, is bycatch.²⁴³ Alverson et al.²⁴⁴ estimated that between 18 and 40 million tons of total harvest are discarded annually by commercial fisheries. Bycatch can significantly alter ecosystems.²⁴⁵ In East Asia, a considerable quantity of fish derived from bycatch is utilized by the aquaculture sector.

This bycatch is transformed into fishmeal and fish oil, which are then integrated into the diets of farmed shrimp and fish.²⁴⁶

The swift expansion of the aquaculture sector, which depends significantly on fishmeal as a key protein ingredient in formulated feed, has fueled both demand and price escalation for this commodity. Concerns have been raised about the potential for overfishing as a result.^{247,248}

DISEASE TRANSMISSION

Intensive aquaculture practices create conditions conducive to disease proliferation, posing a significant risk of spillover into wild fish stocks, which can threaten their health and sustainability.²⁴⁹ The introduction and spread of pathogens through imported aquatic species have exacerbated disease outbreaks in the Philippine aquaculture industry. A notable case is the outbreak of Taura Syndrome Virus (TSV) in *Litopenaeus vannamei* shrimp farms across Bulacan, Batangas, Bohol, and Cebu. Vergel et al.²⁵⁰ detected the virus in cultured shrimp using RT-PCR, confirming its presence with a characteristic 200-base-pair band. TSV, classified under the Dicistroviridae family, was initially identified as a major cause of mortality in *L. vannamei* aquaculture and primarily spreads through the importation of infected post-larvae and broodstock.²⁵¹ Despite previous bans on *P. vannamei* importation, unauthorized introductions have heightened concerns about transboundary disease transmission.²²¹ Tilapia farming in the Philippines has also been affected by disease outbreaks. In Taal Lake, Nile tilapia (*O. niloticus*) cultured in aquaculture cages exhibited significantly higher levels of micronuclei and nuclear abnormalities than those in non-aquaculture sites, suggesting genotoxic stress likely linked to water quality deterioration and pathogen exposure.²⁵² Additionally, *Salmonella* contamination has been detected in 16.26% of aquaculture commodities from Manila Bay farms, with filter-feeding shellfish like *Perna viridis* (green mussel) and *Crasostrea iridalei* (oyster) showing high contamination rates, underscoring the role of aquaculture systems in accumulating and spreading pathogens.²²⁰ These cases highlight the urgent need for stringent biosecurity measures, improved quarantine protocols, and responsible aquaculture management to mitigate disease risks associated with intensive aquaculture and the importation of aquatic species in the Philippines.

RECOMMENDED MITIGATIONS

Aquaculture has become an increasingly important source of seafood, but its expansion has led to significant environmental impacts. To ensure sustainability, effective mitigation strategies are essential. This section deals with mitigation measures targeting habitat destruction, sediment alteration, water pollution, and biodiversity impairment.

FOR HABITAT DESTRUCTION

SITE SELECTION AND HABITAT CONSERVATION

Careful site selection prevents habitat destruction, protecting mangroves, seagrasses, and coral reefs. In the Philippines, Geographic Information System (GIS) and remote sensing help identify suitable locations, reducing environmental impacts. Zoning laws and buffer zones maintain water quality and biodiversity.¹⁴ Enforcing science-based site selection supports sustainable aquaculture growth while ensuring critical ecosystems remain intact, balancing food production with environmental conservation.

INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA)

IMTA combines finfish, shellfish, and seaweeds in a single system to enhance sustainability by reducing waste and improving water quality. In the Philippines, successful IMTA systems include milkfish (*C. chanos*), oysters (*Crassostrea* spp.), and seaweeds (*Kappaphycus* spp.) in coastal farms, which have shown improved nutrient cycling and reduced environmental impact.²⁵³ Studies in Bolinao, Philippines, demonstrated that integrating seaweeds with finfish reduced nitrogen levels, promoting ecosystem balance.¹²⁰ These examples highlight IMTA's potential to enhance biodiversity, increase productivity, and support sustainable aquaculture in the Philippines.

HABITAT RESTORATION

Community-based mangrove and seagrass restoration projects, supported by governmental and non-governmental organizations, can restore degraded habitats. Planting and nurturing mangrove seedlings and seagrass transplants can help restore coastal ecosystems, providing valuable ecosystem services such as shoreline protection, carbon sequestration, and nursery grounds for fish and other marine organisms.²⁵⁴ The Philippine government has implemented several mangrove restoration projects, notably the Bakhawan Eco-Park in Kalibo, Aklan, established in 1990 to combat flooding and storm surges. This 220-ha mangrove forest is acclaimed as the nation's most successful reforestation effort.^{255,256} Another example is the Balian-gao Protected Landscape and Seascape in Misamis Occidental, covering 294.10 ha of mangroves, seagrass beds, and coral reefs, effectively preserving biodiversity and supporting fisheries.^{257,258} These initiatives highlight the effectiveness of habitat restoration in enhancing coastal resilience and ecological health.

BUFFER ZONES

Establishing buffer zones around aquaculture sites can protect adjacent natural habitats by absorbing potential pollutants and preventing habitat encroachment. Mangrove buffer zones, for example, can filter pollutants from aquaculture effluents, reducing their impact on coastal waters. In the Philippines, the DENR issued Administrative Order No. 76 in 1987, establishing buffer zones in coastal and es-

tuarine mangrove areas to protect these vital ecosystems. Additionally, Fishpond Lease Agreements (FLAs) require lessees to maintain mangrove buffer zones between fish ponds and the ocean, ensuring environmental sustainability in aquaculture practices. These initiatives demonstrate the government's commitment to integrating mangrove conservation with aquaculture development.⁴⁷

FOR DETERIORATED SEDIMENTS

MONITORING AND REMEDIATION

Regular monitoring of sediment quality parameters, such as redox potential, total sulfides, organic carbon, and total organic nitrogen, can detect changes early and allow for timely management actions. This involves routine sampling and analysis of sediment to track parameters and identify potential impacts on benthic communities.²⁵⁹ The BFAR encourages farms to adopt these practices to maintain sediment quality. Sediment remediation techniques, such as bioremediation using microorganisms or plants to degrade contaminants and physical removal of contaminated sediments, can also be effective strategies to restore sediment health.^{260,261}

OPTIMIZED FEEDING PRACTICES

Precise feeding strategies in finfish aquaculture involve using formulated feeds with high digestibility, adjusting feed rations based on fish biomass, and employing feeding methods that reduce waste.²⁶² Techniques include feeding trays, automatic feeders, and real-time monitoring of fish behavior to prevent overfeeding. The "clean and clear feeding method" promoted by SEAFDEC-AQD recommends feeding in small, controlled amounts at scheduled intervals to ensure maximum consumption. Additionally, demand feeding—where fish trigger feed release—further minimizes waste. These strategies improve feed conversion efficiency, reduce organic sedimentation, and maintain water quality, supporting sustainable aquaculture practices.

MACROFAUNA AND OXYGEN-RELEASING COMPOUND (ORC)

Large polychaetes, such as Eunicide worms, can enhance both proteolytic activity and redox conditions, suggesting their potential contribution to nutrient cycling and sediment remediation. Santander-de Leon et al.¹⁵⁹ found that these worms can help degrade organic matter and improve sediment quality. Additionally, oxygen-releasing compounds (ORCs) like magnesium peroxide (MgO_2) can effectively reduce sulfide levels and sulfate-reducing bacteria in organically polluted aquaculture sediments. This suggests that ORCs could be a potential mitigation strategy for addressing the negative impacts of excess feed pollution on sediment quality.²⁶³

FOR WATER POLLUTION

MANGROVE REFORESTATION

Mangroves act as natural biofilters, trapping sediments and absorbing nutrients from aquaculture effluents. Community-led mangrove restoration projects in the Philippines, such as those in Aklan province, have shown significant benefits. The Bakhawan Eco-Park in Kalibo, Aklan, is a prime example where reforestation efforts have enhanced local biodiversity, provided coastal protection, and improved water quality by filtering out pollutants from nearby aquaculture farms.²⁵⁶

REDUCED ANTIBIOTIC USE

Environmentally friendly alternatives to antibiotics in aquaculture include probiotics, prebiotics, phytobiotics, immunostimulants, and bacteriophages. Probiotics (e.g., *Lactobacillus* spp., *Bacillus* spp.) enhance gut health and disease resistance,^{264,265} while prebiotics (e.g., inulin, oligosaccharides) promote beneficial microbial growth.²⁶⁶ Phytobiotics, such as plant-derived extracts (e.g., garlic, turmeric), possess antimicrobial properties.²⁶⁷ Immunostimulants (e.g., beta-glucans) strengthen fish immunity, reducing disease susceptibility.^{268,269} Bacteriophages selectively target harmful bacteria without disrupting microbiota^{270,271}). These alternatives, contribute to sustainable aquaculture by reducing antibiotic dependence and mitigating antimicrobial resistance.²⁷²

BIOSECURITY MEASURES

Biosecurity in aquaculture refers to a set of preventive measures designed to reduce the risk of introducing and spreading pathogens, parasites, and antibiotic-resistant genes in aquatic farming systems.²⁷³ These measures include quarantine, water filtration, disinfection, controlled stocking density, and pathogen screening to ensure a disease-free environment. Finfish (e.g., tilapia, milkfish, and grouper) farms commonly adopt biosecurity strategies to prevent outbreaks like viral nervous necrosis (VNN) and bacterial infections. Recirculating aquaculture systems (RAS), hatcheries, and open-water farms implement biosecurity protocols, including water quality management, controlled feeding, and restricted farm access, to minimize disease transmission and maintain sustainable production.²⁷⁴ In seaweed aquaculture in the southern Philippines, seaweed farmers also practice and follow biosecurity measures to reduce pest and disease occurrence.⁹⁴

COMMUNITY-BASED COASTAL RESOURCE MANAGEMENT (CBCRM)

Engaging local communities through CBCRM ensures sustainable aquaculture practices, promotes awareness and education on the impacts of aquaculture, and fosters a sense of ownership among local stakeholders. CBCRM initiatives can help develop and implement effective water

quality management plans and monitor compliance with environmental regulations.²⁷⁵

FOR IMPAIRED BIODIVERSITY

GENETIC DIVERSITY

Hatcheries should use diverse broodstock to maintain genetic diversity and avoid inbreeding. This can help ensure the resilience of aquaculture populations to diseases and environmental changes. The National Integrated Fisheries Technology Development Center (NIFTDC) under BFAR promotes genetic diversity in aquaculture by providing guidelines and training on best practices for broodstock management.²⁷⁶

INVASIVE SPECIES PREVENTION

Strict regulations and quarantine protocols are crucial for precluding the introduction of non-native species, which can competitively exclude indigenous biota and destabilize ecosystem equilibrium. The BFAR implements biosecurity protocols and regular inspections to ensure that only approved aquaculture species are cultured. Additionally, public awareness campaigns are conducted to educate farmers about the risks of invasive species and the importance of adhering to regulations.^{277,278}

MINIMIZING COMPETITION WITH WILD POPULATIONS

Integrated approaches, such as sea ranching and restocking native species in the wild, can help balance the ecosystem and reduce competition between farmed and wild populations. The Philippine government supports community-based fishery resource management programs that include restocking efforts and habitat rehabilitation projects.²⁷⁵ Furthermore, the use of IMTA systems can help create a more sustainable and environmentally friendly aquaculture practice by combining different species that can coexist without competing for the same resources.²⁷⁹

ADDRESSING ANTIBIOTIC USE

RESPONSIBLE ANTIBIOTIC USE

Implementing guidelines and best practices for antibiotic use can help minimize the selection pressure for resistant bacteria. This includes using antibiotics only when necessary, following appropriate dosage and treatment regimens, and avoiding the overuse of antibiotics for disease prevention.²⁸⁰⁻²⁸² To guarantee the safety of aquatic products and comply with regulations, both aquaculture professionals and ornamental fish enthusiasts must seek guidance from regulatory agencies or veterinarians regarding approved chemical use and proper application. Observing prescribed withdrawal periods is crucial to prevent harmful chemical residues in food.²⁸³

SURVEILLANCE AND MONITORING

The Philippine government actively promotes surveillance programs to monitor antibiotic use, resistance, and residues in aquaculture. The Inter-Agency Committee on Antimicrobial Resistance (ICAMR) oversees the National Action Plan on AMR,²⁸⁴ while BFAR implements the National Residue Control Program and antimicrobial resistance surveillance.¹⁶⁵ These initiatives track antibiotic sales, monitor resistance in aquaculture species, and ensure compliance with safety standards. Training programs educate stakeholders on responsible antibiotic use, safeguarding public health and aquatic ecosystems.

RESEARCH AND DEVELOPMENT

Investing in research to develop new antibiotics, alternative treatments, and sustainable aquaculture practices is crucial for mitigating the dual threats of antibiotic resistance and ecological sustainability. This includes research on the development of novel antibiotics with reduced resistance potential, the identification of natural compounds with antimicrobial properties, and the optimization of aquaculture production systems that minimize the need for antibiotics.

By implementing these mitigation strategies, aquaculture can become a more sustainable and environmentally friendly industry, contributing to global food security while protecting aquatic ecosystems.

FUTURE PROSPECTS AND OUTLOOK

The future of Philippine aquaculture hinges on its ability to strike a delicate balance between economic growth and environmental sustainability. While the sector has undoubtedly contributed to the nation's food security and economic development, its potential to harm delicate marine ecosystems cannot be overlooked. To ensure a sustainable future, a multifaceted approach is necessary.

SUSTAINABLE AQUACULTURE PRACTICES

Sustainable aquaculture practices, such as integrated aquaculture-agriculture systems and RAS, offer promising solutions to minimize the sector's environmental footprint. These innovative techniques can reduce water usage, minimize waste, and enhance overall efficiency. By integrating aquaculture with agriculture (aquaponics), farmers can optimize resource utilization and reduce the need for external inputs. Additionally, recirculating aquaculture systems allow for efficient water use and nutrient recycling, minimizing pollution and reducing environmental impact.

STRICT ENVIRONMENTAL REGULATIONS

Strict environmental regulations are imperative to prevent further degradation of marine ecosystems. Limiting aquaculture expansion in sensitive areas, such as mangroves and seagrasses, can help protect these vital ecosystems. Implementing stringent water quality standards and monitoring water pollution levels can ensure that aquaculture activ-

ities do not compromise water quality. Furthermore, promoting responsible waste management practices, such as proper disposal of aquaculture waste, can mitigate pollution and protect marine biodiversity. All aquaculture professionals and farmers are encouraged to abide by the existing Philippine regulations.

COMMUNITY ENGAGEMENT

Engaging local communities in aquaculture development is essential for building trust, ensuring equitable benefit-sharing, and promoting sustainable livelihoods. By involving local communities in decision-making processes, their knowledge and expertise can be harnessed to develop sustainable aquaculture practices that are culturally appropriate and socially acceptable. Additionally, providing training and technical assistance to local communities can empower them to adopt sustainable practices and improve their livelihoods.

INTERNATIONAL COOPERATION

International cooperation plays a crucial role in addressing global challenges, including the environmental impacts caused by aquaculture. By collaborating with international organizations and other countries, the Philippines can access valuable knowledge and resources, share best practices, and promote responsible trade. International cooperation can also facilitate the development of global standards for sustainable aquaculture, ensuring that Philippine aquaculture products meet high environmental and social standards.

By embracing these strategies, the Philippines can establish itself as a global leader in sustainable aquaculture, ensuring that the sector continues to contribute to the nation's economy and well-being while safeguarding its precious marine resources.

CONCLUSION

Based on the synthesis of the study, aquaculture in the Philippines presents a complex interplay of economic benefits and environmental challenges. While the sector has undoubtedly contributed to the nation's food security, livelihood opportunities, and economic growth, its unsustainable practices have led to significant environmental degradation. Environmental degradation associated with aquaculture in the Philippines includes habitat destruction, water pollution, and biodiversity loss. The conversion of coastal areas, such as mangroves and seagrass beds, into aquaculture ponds and other culture systems can lead to significant habitat loss and biodiversity decline. Additionally, the discharge of nutrients, antibiotics, and other pollutants from aquaculture operations can degrade water quality, leading to harmful algal blooms and oxygen depletion. Furthermore, the introduction of non-native species, often associated with aquaculture, can disrupt local ecosystems and outcompete native species. In short, the Philippine aquaculture industry, while significant to the country,

faces several environmental challenges that not only potentially affect the environment but also pose risks to the future of the industry and consumer health. To ensure the long-term sustainability of Philippine aquaculture, a holistic approach is necessary. This involves implementing stringent environmental regulations, promoting sustainable aquaculture practices, investing in research and development, and fostering strong community engagement. By striking a balance between economic growth and environmental protection, the Philippines can secure a future where aquaculture continues to thrive while safeguarding its valuable marine resources.

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COMPETING OF INTEREST – COPE

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