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Development of Mexican and Global Aquaculture as a Sustainable Activity

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Abstract: This review evaluates the trajectory and sustainability of the global and Mexican aquaculture industry. Globally, the sector is experiencing rapid growth, catalyzed by evolving consumption patterns and technological advancements. Notwithstanding the benefits, environmental concerns necessitate an urgent shift towards sustainable practices. The focus then narrows to Mexico's aquaculture, tracing its history from the late 19th century. With an emphasis on species diversification, the country's sector demonstrates resilience and potential, with an impressive yield of 249,613.71 tons in 2021 despite regional consolidation. However, persistent challenges such as technological limitations, funding shortages, and access to quality seeds hinder progress. Risks, including disease outbreaks, negative environmental impact, economic volatility, regulatory compliance, and climate change, further underscore the need for sustainable strategies. With government support and unique geographical and climatic advantages, Mexico shows promise for a significant % growth projection of 25% over the next five years. This review underscores the importance of embracing technological innovation, implementing sustainable practices, and enacting supportive legislation for the long-term success of the aquaculture sector worldwide, with a particular focus on Mexico.

Keywords: aquatic ecosystems; aquatic environment; pisciculture; water pollution; and water resources

1. Introduction

Aquaculture embodies the economic, social, and cultural activities associated with the breeding and cultivation of aquatic organisms. This process necessitates human intervention to augment and ensure the production of highly demanded species, such as shrimp, catfish, tilapia, and trout [1-3]. The population of these aquatic organisms must be nourished and shielded from predators in a controlled environment while managing their growth effectively. Consequently, aquaculture practices differ regionally; for instance, in Vietnam, freshwater from paddy fields is used for cultivation, while in Ecuador, saltwater shrimp are produced in ponds, and in Norway and Scotland, cages are utilized along the coastlines for salmon farming [4-6].

Freshwater species, including tilapia and carp, which require minimal water and entail low maintenance costs, are considered the most valuable in aquaculture [7]. Aquaculture stands as a viable alternative for food supply because, along with capture fisheries, it mirrors food security and forms an integral part of a nation's economy. It contributes to national food security, generates foreign exchange, creates job opportunities in underprivileged areas, and aids in poverty reduction [8,9].

The products derived from aquaculture are rich in animal proteins, thereby contributing to the growth and stability of the food system, as they form part of one of the healthiest food sources available. Among the most widely produced fish products globally, they serve as a significant source

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of animal protein and are consumed by 17% of the global population. However, in less developed countries, the per capita consumption of these products might surpass 50% [10].

2. Aquaculture Worldwide

Aquaculture has been practiced for at least two centuries in its most rudimentary form. However, intensive farming systems akin to terrestrial animal production have only emerged more recently, around 1950 [11]. By 2016, global production of aquatic organisms had reached approximately 170.9 million tons, worth around 250,000 million dollars [12, 13]. A substantial part of this production, just over 110.2 million tons, was attributed to aquaculture, accounting for about 64% [14]. These figures underscore the significant role of aquaculture in bolstering global food security, a trend set to continue [2, 15].

Since 2011, the production of aquatic organisms from capture fisheries has remained relatively stable, averaging nearly 93 million tons annually. However, aquaculture production increased by 48 million tons over the same period, demonstrating a substantial growth of 78% [12, 16]. The Asian continent has made the most significant advancements in developing aquaculture systems, with China leading the charge, boasting a production of nearly 64 million tons in 2021. Additionally, countries including Indonesia, India, Vietnam, Bangladesh, the Philippines, Korea, Egypt, Norway, and Japan each produced over a million tons [17].

Regarding the groups of species that primarily contribute to aquaculture production, fish are the most significant, contributing 54,091 million tons (49.08%), followed by crustaceans with 7,862 million tons (7.13%), mollusks with 17,139 million tons (15.55%), and aquatic plants with 30,139 million tons (27.35%). Other organisms, such as frogs and invertebrates, accounted for 939 thousand tons (0.85%) of the overall production [12].

3. Aquatic Byproducts

Of the total production of 171 million tons of aquatic organisms derived from fisheries and aquaculture, approximately 88% is allocated directly for human consumption. This consumption involves various products, from fresh fish sold at local markets to processed items in supermarkets worldwide, contributing significantly to global nutritional security [12]. The remaining 12% of the aquatic organisms are transformed into secondary products such as fishmeal and fish oil [18]. These byproducts have found a variety of applications beyond human consumption. For instance, they serve as essential components in livestock and poultry feed, contributing to the overall efficiency of the agriculture sector. Fishmeal and fish oil are also integral to aquaculture feed, driving the sector's continuous growth and development. Decking products and the pharmaceutical industry also utilize these derivatives, promoting various health and lifestyle benefits.

This dependency on aquaculture and terrestrial species breeding on fishmeal raises significant sustainability concerns. Fishmeal production is inherently linked to the health of wild fish populations and the overall marine ecosystem. In 2021, out of the total 24 million tons of fishmeal produced, 5 million tons were allocated to non-food activities [19]. Such high demand can put undue pressure on marine resources, potentially leading to overfishing and ecological imbalance.

Given these circumstances, it's imperative to investigate alternative protein sources that can be used in feed production for aquaculture and terrestrial animal farming. Implementing these alternatives could alleviate some environmental pressure and help ensure the longevity and sustainability of the aquaculture industry and related sectors [19]. Efforts to discover and optimize such alternative sources should be a priority, engaging researchers, industry players, policymakers, and consumers in building a more sustainable future.

4. Alternatives in Aquaculture Feed

The aquaculture industry's connection to fishmeal use is profound [20]. Fishmeal, which contains a complex matrix of protein, fatty acids, minerals, and vitamins and a well-balanced spectrum of essential amino acids, ranks as the most expensive commercial unprocessed protein [21].

Despite its nutritional richness, over-reliance on fishmeal has raised significant sustainability concerns due to its pressures on marine ecosystems. Consequently, there has been a mounting necessity to innovate alternatives that improve fish health and nutrition and enhance environmental sustainability.

This demand for alternative feeds has prompted localized research efforts. These initiatives focus on specific regional needs and account for the unique dietary requirements of different species. Such a diversified approach is crucial because no single alternative feed ingredient can universally replace fishmeal due to the varied nutritional needs of aquatic species [23]. This attention to tailored solutions is integral to developing sustainable and effective feeding strategies.

Feed generally represents the most significant expenditure in the aquaculture production chain, typically accounting for up to 60% of operating costs [20-22]. This substantial financial burden further emphasizes the need for sustainable, cost-effective alternatives. Several promising avenues have been explored, including plant-based feeds, insect-based proteins, single-cell proteins, and byproducts from the food industry. Moreover, advances in biotechnology offer potential solutions, such as developing genetically modified plants with higher levels of critical nutrients [24, 25].

It's crucial, however, that these alternatives ensure optimal fish health and growth while also considering the broader environmental impacts, ensuring that the drive towards more sustainable aquaculture feed solutions does not inadvertently result in other ecological problems. Therefore, the search for alternatives in aquaculture feed needs to be an ongoing, multidisciplinary effort involving stakeholders from various fields, from marine biology and nutrition science to environmental policy and economics. While research continues into the viability of these alternative feed sources, it's equally important to study their potential impacts on the health and taste of the fish, as well as the overall productivity of the aquaculture operation. As a case in point, plant-based feeds, while a promising and sustainable alternative, have been found to potentially affect fish growth rates and the final taste of the product [26].

Insect-based proteins present another viable alternative, as insects are high in protein, reproduce quickly, and can be farmed sustainably. However, the mass production of insects is still in its nascent stages and requires further technological advancements to be economically feasible on a large scale. Single-cell proteins derived from yeast, fungi, and algae are yet another area of research with significant potential. These proteins are sustainable, can be produced with minimal environmental impact, and contain essential nutrients required by fish. However, much like insect-based proteins, the large-scale production of single-cell proteins faces challenges related to cost and production efficiency [27, 28].

Food industry byproducts, such as spent grains from breweries or leftover pulp from juice processing, can also be used as a source of fish feed. Not only does this approach reduce waste, but it also offers a cost-effective and sustainable solution. Nevertheless, these byproducts vary significantly in their nutritional content and must be appropriately processed and mixed to meet the specific dietary requirements of different fish species [29]. Advances in biotechnology, such as developing genetically modified plants with enhanced nutritional profiles, could provide a viable alternative to fishmeal. These genetically modified crops can be engineered to produce higher levels of proteins or specific amino acids, which could contribute to improved fish health and growth. However, using genetically modified organisms (GMOs) in fish feed is subject to strict regulations and requires extensive safety testing before it can be widely adopted [30].

These considerations underscore the complexities involved in developing alternatives to fishmeal. It's not just a matter of finding a new source of protein. These alternatives must be sustainable, economically viable, and nutritionally complete. Moreover, they must be produced and utilized in a way that respects local ecosystems and global biodiversity. As such, finding these solutions requires a holistic, collaborative approach, drawing on the expertise of various stakeholders, including researchers, aquaculture practitioners, policymakers, and consumers.

5. Exclusive Utilization of Byproducts from the Aquaculture Sector

Using byproducts from the aquaculture sector provides an excellent opportunity for industry sustainability and cost-effectiveness. An example of this is fish silage and shrimp waste, which, as demonstrated in recent studies, could replace up to 75% of fishmeal without compromising the growth and health of the fry, making it an economically viable alternative [31,32]. However, there are still challenges to overcome with this approach. The silage, lacking preservatives, is prone to fermentation, which can affect its overall quality. Additionally, the acidity of the feed, a byproduct of the silage production process, can deter fish from consuming it due to suppressed appetite [33].

Fishmeal made from species like *Gambusia affinis* or *Atherina boyeri* has also shown promising results, with the potential to replace up to 50% of commercially used fishmeal without affecting feed efficiency or the health of the aquatic organisms [34,35]. Economic analyses have endorsed this alternative, acknowledging its potential benefits in terms of both cost and sustainability. In addition to fish silage and specific species' fishmeal, other aquaculture byproducts are being explored as possible ingredients in fish feed. These include various forms of seafood processing waste, such as shells, heads, and viscera, which are rich in protein and other nutrients [36,37]. After appropriate processing, these wastes can supplement or replace conventional aquaculture feed ingredients.

The use of microalgae, a byproduct of the aquaculture sector, is also worth noting. Microalgae are rich in proteins, lipids, and essential fatty acids, which makes them an excellent supplement or replacement for conventional fishmeal [38]. The culture of microalgae in waste streams from aquaculture operations also provides a means of waste treatment, creating a closed-loop system that is both economically and environmentally sustainable.

6. Use of Terrestrial Animal Proteins

The exploration of terrestrial animal proteins as substitutes for fishmeal is ongoing, including byproducts such as food waste, blood, feathers, meat, and bone meal [39,40]. However, these substitutes present a challenge due to their inadequate amino acid profiles. They often contain insufficient essential amino acids like lysine, isoleucine, and methionine, vital for aquatic species [41].

Once this nutritional deficiency is rectified with the help of dietary supplements, these terrestrial animal protein sources can potentially replace up to 75% of fishmeal, providing a more cost-effective solution. Despite their potential, these alternatives have yet to be deemed fully efficient, primarily due to the additional requirement for supplement integration to meet nutritional needs [19].

7. Use of Vegetable Proteins

7.1. Oil plants

Among the various sources of vegetable proteins, soy flour stands out, which has a high protein content and a complete amino acid profile. Despite this, it has deficiencies in methionine, lysine, and cysteine content. Soy flour also contains antinutrients such as trypsin proteases, antivitamins, and inhibitors such as lectin phytohemagglutinin [42]. However, these elements can be destroyed by heat treatment. Thus, the intervention of this substitute had excellent efficiencies in partial substitutions of up to 75%. The success of the substitution will depend on the species, growth phase, and the minimum requirements for optimal growth, especially since the number of minerals present in soybean meal can be a limitation. Cottonseed meal is an alternative to tropical and subtropical regions due to its high protein available at a low price [43,44]. The problem that arises is that the protein and its quality will depend on the management of the seed and its procedure, reaching 26-54% despite having a low amino acid profile in the content of cysteine and lysine, and this has a minimum efficiency of 50% up to 100% assimilation in aquatic species [45].

7.2. Aquatic Plants

Among various aquatic plants studied for their potential as alternative feed sources in aquaculture, water duckweed (Lemna spp.) stands out due to its high vegetable protein content,

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reaching up to 45%. The plant also boasts an adequate amino acid profile, making it nutritionally suitable for many aquatic species. Furthermore, it has a robust mineral profile, enhancing its nutritional value [46, 47].

In specific production systems, water duckweed has even been used as the sole nutrient source, demonstrating its potential as a primary feed ingredient. However, to achieve optimal yield without adverse effects and maintain economic viability, a 50% substitution rate is ideal [48]. Water duckweed is not the only aquatic plant showing promise in this regard. Other aquatic plants, such as water ferns (Azolla spp.), have also demonstrated benefits, particularly in the early stages of fish development, known as the fry stage [49,50]. These plants offer nutritional benefits and contribute to the aquatic environment's overall health by improving water quality.

In addition to water duckweed and water ferns, the use of microalgae, seagrasses, and even invasive aquatic plants like water hyacinth (Eichhornia crassipes) is being explored. They are being studied for their potential to offer a sustainable and readily available source of nutrition for aquaculture [51]. Yet, while using these aquatic plants as potential feed alternatives show promise, further research is needed to understand their nutritional profiles fully, their impact on aquatic organism health, and their overall effects on production systems. This includes long-term studies on growth rates, survival, and product quality when using alternative feeds [52].

7.3. Legumes

Due to their high protein content and availability, legumes are often employed as partial substitutes for cereals in aquaculture feed. For example, Leucaena can contribute up to 30% of the protein in a feed mix, making it a cost-effective and nutritionally valuable substitute [43]. Similarly, beans and corn are frequently utilized alternatives due to their favorable nutrient profiles and availability. However, despite their utility, most legumes display variable amino acid concentrations and can be deficient in specific amino acids, such as arginine, isoleucine, methionine, and threonine. This variability and deficiency can impact the nutritional value of the feed and potentially the growth and health of the aquatic species being farmed. Further studies are needed to fully understand the potential of different legume species in aquatic feeds and optimize their usage [44].

It's also crucial to consider the presence of antinutrients like mimosine in some legume species. Mimosine is a non-protein amino acid found in Leucaena that can be toxic in large amounts. Thus, careful formulation and processing of feeds using such species are required to minimize potential adverse effects [53]. In addition to legumes, certain seeds, such as cassava and corn, have been evaluated for their suitability in aquaculture feeds. These seeds have proven particularly beneficial during the frying phase, with substitutions of up to 25% and 100%, respectively, leading to satisfactory species growth. However, the phytic acid present in these species can affect the bioavailability of minerals, especially if the feed is already deficient in one or more minerals. Moreover, research on novel feed sources, such as insect meal and algae, offers promising alternatives to traditional feed ingredients, particularly in sustainability [54, 55]. By expanding our understanding and use of various feed sources, we can enhance the sustainability and resilience of the aquaculture industry.

7.4. Use of Unicellular Proteins

Using microorganisms, such as algae, fungi, bacteria, cyanobacteria, or yeasts, as alternatives in semi-intensive and intensive feeding systems are gaining attention due to its ability to simplify production, making it cheap and effective [56,57]. These microorganisms can complement carbon sources, such as wheat or rice bran, and optimize the production system using affordable sources. Thus, unicellular proteins are a group of microorganisms used to promote growth and are environmentally friendly, as these bacteria reduce the concentration of ammonia [58].

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8. Aquaculture World and Its Risks

8.1. Monitoring Aquaculture

A thorough and robust monitoring system is crucial for effective management of aquaculture facilities. Such a system should provide the necessary insights to make informed decisions based on various data, including production levels, the extent of farming areas, and environmental impacts [59, 60]. Thus, periodic monitoring is required on multiple scales, ranging from individual production units to the broader ecosystem, to facilitate this decision-making. However, the establishment and execution of such comprehensive monitoring, particularly via cartography-based methods, pose significant challenges. These challenges primarily stem from the high costs of deploying suitable systems, a lack of available infrastructure, limited financing options, and the shortage of skilled personnel [61]. In response to these challenges, the Food and Agriculture Organization (FAO) is working to address these fundamental issues, emphasizing aiding less developed regions. A proposed strategy includes the development of cost-effective technologies that benefit creating species inventories, establishing care systems for cultivable species, and implementing sustainable management practices [62, 63].

Furthermore, these technologies would be integrated into licensing procedures to identify and handle unregistered or illegal operations. They would also offer valuable data for selecting suitable farming sites and evaluating their impact on the ecosystem to mitigate potential environmental damage. Global positioning systems (GPS) are instrumental in locating and recording aquaculture facilities. They enable innovative methods for updating geographic information systems (GIS) and conducting spatial analyses, providing a comprehensive view of aquaculture operations within their environmental context [58, 61]. Advanced technologies like remote sensing, AI-based predictive models, and Internet of Things (IoT) devices are also being explored to augment monitoring efficiency and accuracy. However, their effective implementation requires investment in capacity building, technological infrastructure, and appropriate regulatory frameworks [64].

8.2. Shortage of Decent Work

Poor job quality often correlates with low productivity, a phenomenon whose causes vary widely depending on the work context. Producers face numerous shared challenges within the aquaculture industry, including limited access to formal education. This education gap often restricts service availability and complicates adopting sophisticated markets and advanced technologies [65, 66]. Moreover, inappropriate handling of fish and subpar standards in capture, processing, and storage facilities contribute to significant post-capture losses in production. These factors often culminate in decreased overall production yields [67].

In places like Mexico, families with limited alternative employment opportunities often resort to working in aquaculture, despite low wages and poor working conditions. As the industry continues to expand, there is an increasing risk of resource overexploitation. This overuse could lead to environmental degradation, threatening the livelihoods of many individuals who rely on aquaculture for employment. Addressing the scarcity of decent work in aquaculture requires a comprehensive approach. This strategy should include enhancing access to education and training, developing and implementing advanced technologies, and improving the quality of facilities for fish handling, capture, processing, and storage. These measures will increase productivity and promote the sustainability of the industry and the welfare of communities that depend on it [49].

8.3. Social Protection

Workers within the aquaculture and fisheries sectors, particularly those from vulnerable societal segments, face unique challenges. These individuals often engage in hazardous activities and serve as a crucial income source for the lowest-income demographics, all while lacking sufficient social protection [69]. While some countries offer informal and limited forms of protection, integrating these workers into formal social security systems remains a significant challenge. As a result, these workers

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and their families are exposed to environmental, social, physical, and economic risks. These risks are further exacerbated by migration, sexually transmitted diseases, gender-based violence, and drug abuse [70].

The overexploitation of natural resources is not the only problem these workers face; their profession is also among the most dangerous. Each year, approximately 24,000 workers suffer from illnesses, injuries, and fatalities often linked to extended working hours and fatigue. Despite these substantial risks, the lack of effective enforcement of safety standards exacerbates their plight. To address these issues, enhanced social protection for workers in the aquaculture and fisheries sectors is needed. Potential measures include providing access to healthcare, education, and training programs and implementing occupational health and safety regulations. Such initiatives can help ensure fair treatment and protection of workers' rights in these sectors, thereby contributing to the sustainability of the industry and the well-being of the communities that rely on it [70].

8.4. Climate Change

Climate change is a critical global concern, necessitating the development of adaptive strategies in aquaculture that understand its impact pathways, variability, and potential risks. These encompass but are not limited to, the warming of water bodies, rising sea levels, ocean acidification, and shifts in weather patterns, which could present as extreme fluctuations [71]. The Intergovernmental Panel on Climate Change (IPCC) highlighted in 2014 the significant threats climate change poses to aquaculture. These threats include system vulnerabilities, increased CO2 levels, and the subsequent effects of water acidification on the physiology of various species, impacting their growth, reproduction, and product quality for consumers.

However, global warming might also introduce specific opportunities, such as potentially increasing growth rates and expanding the viable cultivation limits of mass crop species. The research on the most climate-sensitive fish species, from embryonic to adult stages, is particularly compelling. Studies have shown a correlation between temperature changes and factors like growth rate, disease susceptibility, spawning time, and mortality percentages at different developmental stages [72]. Climate-induced metabolic changes could lead to significant economic consequences and health alterations in aquatic organisms. Additionally, modifications to the aquaculture infrastructure will be necessary, driving a need for more specific and adequate feeds [73,74].

8.5. Vulnerability of Species

Assessing the vulnerability of species and environmental systems in aquaculture involves categorizing farms based on their geographical location [75]—be it continental, coastal, or arid tropical—and the density and intensity of their production. Farms can vary significantly in their technological capabilities and production systems even within the same location. This variability can increase farmers' vulnerability, especially concerning supply chain issues. As a result, it is essential to develop alternatives to mitigate these vulnerabilities, employing effective local practices and advanced techniques [76].

These alternatives might encompass the utilization of new biological strains, like salt-resistant catfish, and the refinement of harvesting methods to ensure the quality of the yield. Incorporating technology to enhance fish health and feeding efficiency is also a consideration, including water recycling methods [77, 78].

8.6. Sustainability through the Organization

Fishers and aquaculture farmers frequently operate in basic setups without formal contracts, limiting syndication within this sector and the ability to establish policies. The reliance on intermediaries, linked to value chain mechanisms, is marked by the presence of operators responsible for securing the livelihoods of producers in primary areas of artisanal or industrial sectors [79]. Tailored interventions are needed to maintain communication, as every country and its context are unique [80]. Therefore, the focus should be on creating simple, sustainable, and inclusive chains, with

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particular attention given to small-scale operations to avoid overcapacity in the sector and to prevent economic, environmental, and social disturbances. A pivotal issue in the production chain is the generation of byproducts affecting aquaculture. This raises questions regarding the system's suitability and the use of fishmeal and fish oil, especially when it threatens other species [66, 72].

9. Aquaculture in Mexico

Water has been integral to human settlements and societal advancement throughout history. Its utility spans various domains, including domestic use, livestock watering, agricultural irrigation, aquaculture, power generation, navigation, and recreation. In aquaculture, water is a critical component and a crucial determinant of diversity in climatic conditions and ecosystems. In Mexico, this diversity, driven by the country's unique altitudinal profile, significantly contributes to the aquaculture sector's growth [81]. However, the sector's successful development also hinges on the efficient application of advanced technologies and innovative, modernized, and productive transformation processes [82]. The formal establishment of fish farming in Mexico dates back to the late 19th century, when the Ministry of Development began constructing a fish nursery in Ocoyoacac, State of Mexico. This was marked by the import of a batch of 500,000 rainbow trout fry (Oncorhynchus mykiss) from the United States.

Moreover, the Mexican aquaculture sector's progress is attributed to an array of local species, such as the whitefish, which are adapted to various environmental conditions and suitable for cultivation [83]. It has further been bolstered by the implementation of supportive government policies and programs to develop aquaculture and sustainable fishing, promotes species diversification, and facilitate access to financial resources [84]. Simultaneously, challenges persist, including access to high-quality seeds, lack of technological advancements, insufficient research, and limited funding, which must be addressed to ensure the sector's long-term sustainability.

9.1. Mexican Aquaculture in the Time

In 2008, SAGARPA (The Mexican Ministry of Agriculture and Rural Development) segmented Mexico into five regions for its initiative titled "Diagnosis and Regional Planning of Fisheries and Aquaculture." This initiative aimed to foster sustainable and integrated development of the aquaculture sector, which holds considerable economic and social significance across these regions. However, due to territorial and public policies implemented in Mexico in 2020, these regions were further consolidated into four, potentially owing to restrictions on water use and other factors limiting aquaculture production. Despite this, the sector bounced back robustly in 2021, recording an impressive yield of 249,613.71 tons (Figure 1) across Mexico.

Figure 1. Map of the Mexican Republic with the aquaculture regions division by Mexican public and territorial policies.

Region I, The Pacific North (Red), encompasses five states - Baja California Norte, Baja California Sur, Sonora, Sinaloa, and Nayarit. In 2021, this region collectively produced 195,705.71 tons in live weight, with Sonora and Sinaloa each accounting for 39% of the output. Region II, the South Pacific Zone (Yellow), comprises six states: Chiapas, Jalisco, Colima, Michoacán, Oaxaca, and Guerrero. They collectively contributed 34,599.97 tons in live weight to the aquaculture sector during 2021, with Jalisco leading the region by generating 37% of the production. Region III, the Gulf Zone of Mexico and the Caribbean Sea (Green) includes six states - Veracruz, Tamaulipas, Quintana Roo, Yucatán, Tabasco, and Campeche. Veracruz, in particular, spearheaded production in this region, accounting for 86% of the total production of 17,901.23 tons in live weight. Lastly, Region IV, the Zone of Landlocked States, comprises regions not reliant on aquaculture breeding methods linked to the use of inland waters. This region yielded 1,406.80 tons in live weight, with Estado de Mexico leading the zone by contributing 34% of the overall production [85].

However, the industry does exhibit an over-reliance on just two species: shrimp and tilapia (Oreochromis niloticus), mainly propagated through crossbreeding. To optimize the utilization of marine, brackish, and continental water resources and promote sustainability, species diversification is a critical consideration. Various freshwater fish include Robalo, bass, and catfish, marine fish like Snapper, sea bream, red Snapper, sea bass, horse mackerel, tuna, and mollusks including clams, abalone, and snails. Freshwater crustaceans like freshwater lobster, shrimp, and other groups like Sargassum and ornamental fish were included in Mexican aquaculture in 2021.

During the 1990s, social, political, economic, and environmental factors drove aquaculture activity in Mexico. Legislative amendments and the development of federal government support programs significantly strengthened value chains by initiating better-structured projects and generating crucial socio-economic and environmental data [86]. Despite considerable progress, the aquaculture industry still faces numerous challenges toward achieving complete sustainability. Investment in science and technology is a requisite, fostering a culture that harmonizes economic development with environmental well-being. Even though strides have been made in developing value chains, bureaucratic obstacles impede the establishment of robust relationships among producers, researchers, and government agencies.

9.2. The Journey towards Sustainable Aquaculture in Mexico: A Multi-Faceted Approach

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Achieving sustainability in the aquaculture sector entails more than just environmental conservation. It calls for a holistic approach, combining social, economic, and ecological aspects while ensuring that the benefits are equitably shared across society. Mexico, with its diverse climatic conditions and altitudinal profile, offers a variety of environments suitable for different species. This biodiversity presents an opportunity for sustainable diversification, promoting the cultivation of a range of local species adapted to various environmental conditions, reducing over-reliance on specific species, and enhancing ecological resilience. To address the challenge of access to high-quality seeds, strategies such as the establishment of government-certified hatcheries and seed banks, as well as the promotion of best practices among farmers, could be implemented. This would improve the quality of seeds and boost productivity, contributing to economic sustainability.

Technological advancements can bolster environmental and economic sustainability. The adoption of precision aquaculture technologies, such as sensors and AI, can optimize resource use and reduce waste while contributing to increased yields and profitability. Addressing the economic risks associated with market fluctuations and price volatility requires developing value-added products, diversifying markets, and creating cooperative societies. These measures can stabilize incomes for farmers and encourage sustainable practices. Regulatory compliance is critical to maintaining the social license to operate. Ensuring that aquaculture practices adhere to national and international guidelines on food safety, environmental conservation, and animal welfare will protect the sector from reputational damage and penalties. Lastly, acknowledging climate change as an inevitable challenge, proactive strategies, such as developing climate-resilient species, improving farm infrastructure, and providing insurance schemes, can help ensure the sector's long-term sustainability. Through these multi-faceted strategies, Mexico's aquaculture sector can journey towards a sustainable future, contributing significantly to the country's economy while protecting the environment and society.

9.3. *Mexican Aquaculture and Its Risks*

Like other industries, Mexican aquaculture encompasses risks that could undermine its sustainability and profitability. The following points outline the major risks connected to this sector:

1. Disease Outbreaks: Aquaculture establishments are vulnerable to disease outbreaks which can trigger substantial production losses, compromising the health and welfare of fish and shellfish. Since diseases can rapidly proliferate through water, controlling them is often challenging, particularly in high stocking densities.
2. Environmental Impact: Unregulated aquaculture practices can give rise to adverse environmental effects. Situations such as overcrowding, excessive feeding, and waste discharge can prompt eutrophication and degradation of water quality, impairing the natural ecosystem and impeding production efficiency. Additionally, certain aquaculture practices may detrimentally influence wild fish populations and their habitats.
3. Economic Risks: Aquaculture is a capital-intensive sector necessitating substantial investment in infrastructure, technology, and labor. Factors like market demand fluctuations, price volatility, and production risks - such as disease outbreaks or unfavorable weather conditions - can impose significant financial strain on farmers and industries.
4. Regulatory Compliance: The Mexican aquaculture sector must comply with national and international food safety, environmental conservation, and animal welfare regulations. Non-compliance with these guidelines can lead to penalties, cessation of production, or even reputational damage.
5. Climate Change: As previously noted, climate change can pose considerable risks to Mexican aquaculture. These include temperature shifts, precipitation pattern alterations, sea-level rise, and extreme weather conditions.

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To mitigate these risks, it's recommended for Mexican aquaculture farmers and industries to implement best management practices. These could include regular monitoring and testing, implementation of biosecurity measures, and conducting environmental impact assessments. Moreover, diversifying production systems and investing in research and development could foster greater resilience and adaptability to evolving market dynamics and environmental conditions.

10. Conclusions

Aquaculture, a dynamic sector in constant evolution, faces an ongoing escalation in demand. Juxtaposed with the rising seafood demand, Mexico's capacity to uphold consistent growth in its aquaculture production reveals a burgeoning potential. Projections indicate that over the next five years, Mexican aquaculture is set to experience a growth spurt of over 25%, thereby contributing a significant 52% to fish production dedicated solely to human consumption. The trajectory of these trends underscores the imperative of optimizing every aspect of the value chain. This includes the development of innovative, efficient methodologies and practices, such as technological advancement in equipment and specialized food products that cater to different socio-economic regions and various species' breeding needs. These progressions will act as catalysts in promoting sustainable practices and achieving balanced industry growth.

Positioned advantageously, Mexico holds several keys to emerging as a global powerhouse in aquaculture production, especially cultivating freshwater and shrimp species. A striking example of this advantage is the potential of repurposing its extensive coastal areas, which are unsuitable for agriculture or livestock farming, for aquaculture purposes. Furthermore, with a sprawling coastline extending over 11,211 km, a promising potential area of approximately 236,000 hectares is available for aquaculture. Coupled with the favorable climate across many of the country's regions for cultivating commercially attractive and native species suitable for aquaculture, Mexico stands ready to seize these opportunities and become a prominent seafood provider for major consumer markets. However, realizing this potential necessitates a robust framework of supportive legislation. The federal government should promulgate specific laws that distinguish aquaculture as an activity separate from traditional fishing, fostering its growth and sustainability. Similarly, state governments should legislate in alignment with these principles, introducing policies designed to sustainably develop the aquaculture sector beyond the term of any single government. These legal foundations will help ensure Mexico's aquaculture industry's resilient and sustainable growth.

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