International Journal of Agriculture and Biosciences 2026, 15(1): 29-42.
https://doi.org/10.47278/journal.ijab/2025.151

REVIEW ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Fish Hybridization: A Pathway to Sustainable Seafood Production and Environmental Adaptability

Wan Nur Fatin Syafiqah Wan Nawang [1], Wahidatul Husna Zuldin [1], Nur Nashyiroh Izayati Mastor [1], Norfazreena Mohd Faudzi [1], Kenneth F. Rodrigues [2] and Julian Ransangan [1,*]

[1]Higher Institution Centre of Excellence (HICoE), Borneo Marine Research Institute, Universiti Malaysia Sabah, Jalan UMS, Kota Kinabalu, Sabah 88400, Malaysia
[2]Biotechnology Research Institute, Universiti Malaysia Sabah, Kota Kinabalu 88400, Sabah, Malaysia
*Corresponding author: liandra@ums.edu.my

ABSTRACT

Global seafood demand continues to rise, driven by increasing population, urbanization, and growing health awareness, with global seafood consumption at around 20.5 kg per capita. Overfishing, pollution, and climate change threaten wild fish stocks, driving aquaculture to the forefront of ensuring seafood security. Aquaculture now accounts for over 50% of global fish production and plays a critical role in alleviating pressure on wild fisheries resources. Technological advancements, including improved breeding, enhanced feed efficiency, and improved disease management, have contributed significantly to the growth of aquaculture. However, challenges such as disease outbreaks, environmental sustainability, and economic viability persist. Fish hybridization offers a promising solution, enhancing traits like disease resistance, growth rates, and adaptability to fluctuating environments. Recent studies have shown that hybrid fish outperform wild types in these areas, reinforcing the sustainability of aquaculture systems. Nonetheless, stringent management and monitoring are required to mitigate potential risks, such as unintended release of genetically distinct hybrids and ecosystem disruption. As aquaculture continues to evolve, hybridization is expected to play a crucial role in addressing global food security and meeting the increasing demand for sustainable seafood. This paper reviews success stories in fish hybridization, examines prevailing constraints and challenges, and outlines priority research avenues and policy directions for the field.

Keywords: Seafood security, Fish hybridization, Environmental adaptability, Fish welfare, Regulatory frameworks

Article History
Article # 25-167
Received: 09-Apr-25
Revised: 27-Jun-25
Accepted: 17-Jul-25
Online First: 19-Sep-25

INTRODUCTION

The global demand for seafood continues to rise due to increasing consumer interest. According to the FAO (2020), per capita fish consumption increased from 9.9 to 20.5 kg by 2018, and this trend is expected to persist, driven by growing awareness of the health benefits of seafood and the need to sustain a growing global population. However, wild fish stocks are under significant pressure from pollution, climate change, and overfishing. The FAO's 2020 report on the State of World Fisheries and Aquaculture highlights that nearly one-third of global fish stocks are overexploited, emphasizing the crucial role of aquaculture in ensuring seafood security.

In recent years, aquaculture has played a crucial role in ensuring seafood security by addressing several challenges in the global fish supply. As wild fish stocks face intense pressure from pollution, overfishing, and fluctuating climate conditions, aquaculture offers a sustainable alternative to meet the growing demand for seafood. According to the FAO (2020), aquaculture now contributes more than 50% of the fish consumed worldwide, making it a key player in global food production. This sector has benefitted from technological advancements, such as improved breeding techniques, better feed efficiency, and enhanced disease management.

Cite this Article as: Nawang WNFSW, Zuldin WH, Mastor NNI, Faudzi NM, Rodrigues KF and Ransangan J, 2026. Fish hybridization: a pathway to sustainable seafood production and environmental adaptability. International Journal of Agriculture and Biosciences 15(1): 29-42. https://doi.org/10.47278/journal.ijab/2025.151

A Publication of Unique Scientific Publishers

However, aquaculture still faces significant challenges, including disease outbreaks, environmental sustainability, and long-term economic viability. Fish hybridization has emerged as a promising solution to address these issues, aiming to improve productivity, resilience and sustainability in aquaculture (Lorenzen et al., 2012; Mitra et al., 2023). Researchers from various fields are working to enhance aquaculture production, focusing on creating viable progeny with desirable traits to boost resilience and adaptability to the unpredictable ecological changes (Roberts et al*.,* 2010; Masuma & Aoki, 2023; Ye et al*.,* 2024).

Global Demand for Seafood

FAO (2020) reported that seafoods demand is anticipated to rise by 50% by 2050, driven by increasing population, urbanization and incomes especially in Asia and Africa. The COVID-19 pandemic has underscored the need for robust food systems, with aquaculture proving essential in sustaining seafood supply chains during disruptions (Love et al., 2021; Kelling et al., 2023). This escalating demand underscores the urgent need for sustainable aquaculture practices that can meet international seafood demands while minimizing environmental impacts (Micheli et al., 2014; Ababouch et al., 2023). However, attaining this demand poses a major challenge, for instance, ecological and biodiversity degradation, depletion of wild fish stock, and vulnerabilities in the supply chain (Mangano et al., 2022; Beaugrand et al., 2010). Concurrently, fluctuations in the ecological climate, such as changes in ocean acidity and temperature, lead to disruptions in the distribution of marine species and food webs, affecting biodiversity (Beaugrand et al., 2010; Albouy et al., 2014; du Pontavice et al., 2019; Hodapp et al., 2023).

Overfishing

Human activities, such as overexploitation and ecosystem disturbances, have triggered significant ecological degradation and biodiversity loss. Overfishing, both of targeted and non-targeted species, is a major challenge to food security, contributing to unsustainable fisheries in marine ecosystems and coastal communities (Coll et al., 2008; Cheung et al., 2025). Overfishing remains a critical threat to global fish stocks, with the FAO reporting that 34.2% of fish stocks are currently overfished (FAO, 2020). The overexploitation of wild fish stocks has led to unsustainable fisheries and failures in fisheries management systems (Hilborn et al., 2003; Bastardie et al., 2024). In response, governments are developing more comprehensive management frameworks that focus on holistic ecosystem approaches and species conservation (Murawski, 2000; Naylor et al., 2023). Recent findings indicate that climate change exacerbates the depletion of wild fish populations, affecting fish reproduction, distribution, and growth rates (Free et al., 2019; McKenzie et al., 2021). This persistent decline underscores the growing importance of the aquaculture sector as a sustainable alternative to meet global seafood demands.

Aquaculture Growth

Aquaculture has emerged as a sustainable solution to the depletion of wild fish stocks. It involves the cultivation of fish, invertebrates, and aquatic plants for human consumption. According to the FAO (2022), aquaculture production has seen significant growth, increasing from approximately 15 million tons to over 90 million tons between 2000 and 2020. This growth has been driven by advancements in feed technology, selective breeding programs (Abwao et al., 2021), improved cultivation management techniques, and genetic enhancement (Lu et al. 2019; Manan et al., 2023; Flourizel et al., 2023). As a result, the aquaculture sector plays a crucial role in mitigating the overexploitation of wild fish stocks by contributing to the global food supply chain.

Furthermore, FAO (2020) reported that aquaculture production increased annually by 5.8% from 2000 to 2018, reaching an international production level of approximately 114.5 million tons. With this rapid expansion, the industry is incorporating advancements from various disciplines to further enhance production. Recent innovations, such as the application of biotechnology, the integration of mechanization, and advanced farming systems, have significantly contributed to the efficiency and sustainability of the aquaculture sector (Gladju et al., 2022).

Challenges in Aquaculture

The aquaculture industry faces numerous challenges, such as disease outbreaks (Murray & Peeler, 2005; Leung & Bates, 2013; Sanches-Fernandes et al., 2022), environmental degradation (Pérez, 2003; Martínez-Porchas et al., 2012; Sampantamit et al., 2020; Chiquito-Contreras et al., 2022), and the high costs associated with feed (Suleiman & Rosentrater, 2018). Disease management remains a significant concern, with recent studies indicating a rise in antibiotic-resistant pathogens within aquaculture systems (Miranda et al., 2013; Hossain et al., 2022). Furthermore, the environmental impacts of aquaculture, including habitat destruction, water pollution and reliance on wild fish for feed production, have raised sustainability concerns (Beveridge et al., 2018; Verdegem et al., 2023). One promising solution is the development of fish hybrids, which can enhance the resilience and productivity of farmed fish, reduce the dependency on chemical inputs, and improve the overall efficiency of aquaculture systems (Lorenzen et al., 2012; Zhang et al., 2023).

Fish Hybridization

Fish hybridization has long been practiced, involving the intentional crossing of different species or genera to produce offspring with enhanced traits (Alm, 1955; Hubbs, 1955; Rahman et al. 2013; Adah et al., 2014; Semeniuk et al., 2019). Hybridization can be classified into two types: interspecific, where fish from different species within the same genus are crossed, such as the brown-marbled grouper (*Epinephelus fuscoguttatus*) and giant grouper (*E. lanceolatus*) (Ch'ng & Senoo, 2008) and intergeneric, which involves crossing fish from different genera, like the sympatric kirikuchi char (*Salvelinus japonicus*) and the red-spotted Masu salmon (*Oncorhynchus masou macrostomus*) (Sato et al., 2008).

Despite its potential, fish hybridization faces biological challenges, including sperm recognition barriers, difficulties with sperm-egg penetration, and complications in pronucleus formation (Su et al., 2016; Lu et al., 2023). Researchers have developed strategies to overcome these issues, with hybridization becoming increasingly adopted in aquaculture to improve growth rates, enhance disease resistance, and increase adaptability to environmental changes. Recent advancements in genomic technologies and selective breeding have expanded the potential for hybrid fish breeding, making it a critical tool for enhancing aquaculture's contribution to global food security (Yue & Wang, 2017; Mushtaq et al., 2025).

Hybridization allows for the precise control of genetic traits, with modern molecular biology and genomics enabling the development of hybrids with specific desirable characteristics (Yue & Wang, 2017). These advancements have made hybridization an essential technique for improving the sustainability and performance of farmed fish. Artificial hybridization has also gained traction as an adaptation mechanism in fields such as ecology, conservation, and evolution, helping species adapt to fluctuating environments and promoting ecosystem resilience (Krasnovyd et al., 2020; Bartley, 2021). Studies show that hybrid fish often exhibit greater genetic variability, making them more resilient to stressors such as ocean acidification, climate change, and salinity fluctuations (Jones et al., 2018; Sundin, 2023).

Environmental changes have driven the evolution of species, but some now face endangerment due to these pressures. Fish hybridization offers a solution by creating offspring with greater adaptability to environmental challenges, such as improved growth and disease resistance (Lorenzen et al., 2012). These hybrids are valuable in sustainable aquaculture practices (Kamal & Mair, 2005; Sonesson et al., 2023), especially as the aquaculture industry seeks ways to meet rising demand for protein while managing ecological impacts.

Hybridization also plays a role in conservation by restoring genetic diversity in endangered species through the introduction of strains well-adapted to fluctuating native habitats (Reisenbichler et al., 2003). However, hybridization carries risks, such as potentially harming local native species and leading to genomic extinction in some cases (Muhlfeld et al., 2014). Researchers emphasize the need for careful monitoring and management of hybrid populations to prevent negative impacts on wild populations (Harbicht et al., 2014; Hoffmann et al., 2021).

Traditionally, selective breeding for broodstock has focused on selecting desirable morphological traits, which is time-consuming and uncertain in its outcomes. In contrast, hybridization offers a more efficient method for increasing genetic diversity and improving traits in progeny (Harbicht et al., 2014; Salgotra and Chauhan 2023). Early hybridization efforts in aquaculture, such as tilapia (*Oreochromis* spp.) hybrids (Pullan & Smith, 1987), have paved the way for more recent developments, like the hybrid catfish (*Ictalurus punctatus* × *Ictalurus furcatus*), which has gained widespread adoption in the U.S. due to its superior growth rates and disease resistance (Dunham et al., 2020).

Fish hybridization, which began as a scientific curiosity in the 1880s (Green, 1881; Day, 1882), has evolved into a critical tool for aquaculture and conservation. Early experiments by Alm (1955) on the Salmonidae family laid the foundation for modern hybridization techniques. Although initial hybrids were often less viable than purebreds, continued research has addressed challenges such as hatchability, larval development, and growth rates (Blanc and Chevassus, 1979; Chevassus, 1979). Today, hybridization is recognized as a valuable method for enhancing aquaculture productivity and ecological resilience (Salgotra and Chauhan 2023).

Fish Hybridization Techniques

Numerous studies on fish hybridization have been conducted to advance the aquaculture industry. The primary objective is to enhance specific desirable traits, such as disease resistance, adaptability to diverse ecological and biological environments, lower feed conversion ratios and improved growth and survival rates (Devlin et al., 2015; Robinson et al., 2017; Cook et al., 2000). In earlier decades, fish hybridization primarily focused on broodstock selection and induced breeding through artificial insemination, but managing desirable traits from broodstock proved challenging. However, with the complexities of genetic variation, researchers have adopted innovative approaches, introducing genetic engineering as a solution (Munday et al., 2013; Jones et al., 2018). The use of genetic engineering, particularly CRISPR-*Cas*9, has been successfully implemented in hybrid fish breeding to enhance specific traits and develop improved strains, contributing to the growth of innovative aquaculture (Lu et al., 2021; Roy et al., 2022). This paper explores the techniques used in fish hybridization for aquaculture.

Genetic and Biological Implications of Fish Hybridization

Genetic Diversity

Due to the depletion of wild fish stocks, genetic biotechnologists have developed new variations that improve growth rates, disease resistance, and adaptability to environmental fluctuations. These enhanced traits, often referred to as hybrid vigor, are the result of increased genetic diversity. Hybrid vigor, or the superiority of hybrid offspring over their parental species, is well-documented, with hybrid progeny exhibiting better qualities than their parents (Devlin et al., 2015; Robinson et al., 2017; Cao et al., 2022). The increased genetic diversity offers significant advantages for breeding programs by enabling the manipulation of desirable traits to improve stock quality (Zhang et al., 2023). However, while hybridization can increase genetic diversity, improper management can lead to inbreeding depression, where backcrossing with parental species can result in reduced fitness, lower reproduction rates, and genetic expression issues (Reed et al., 2015). Therefore, effective breeding strategy management is essential to limit the risks and maximize the benefits of hybridization (Luo et al., 2014).

Over time, the genomes of fish hybrids may be subject to genetic drift, which results from random changes in allele frequencies and genome segregation. This drift can alter the genetic population and impact the ecological performance and biodiversity of hybrid fish (Devlin et al., 2015; Robinson et al., 2017). In aquaculture, hybridization enhances genetic diversity, contributing to increased resilience in the face of environmental fluctuations and biodiversity changes. Hybrid populations have been shown to be more resilient to diseases and environmental changes due to their greater genetic variation (Sonesson et al., 2023). Recent studies confirm that hybrid fish often possess greater genetic variation than purebred strains, which improves survival and adaptability to changing environments (Zhu et al., 2021). This genetic diversity is critical for maintaining robust and productive aquaculture systems, as it enables populations to adapt to emerging challenges like climate change and new diseases.

Growth Rates and Efficiency

One of the key advantages of hybrid fish breeding is the potential for enhanced growth rates and improved feed conversion efficiency. Recent studies have shown that hybrid tilapia (*Oreochromis* spp.) exhibit faster growth and greater efficiency compared to purebred strains, making them a more cost-effective choice for aquaculture operations (El-Sayed & Kawanna, 2021). Likewise, newly developed carp hybrids (*Cyprinus carpio* × *Carassius auratus*) have demonstrated superior growth performance and increased disease resistance, further highlighting the potential of hybridization to boost productivity in aquaculture (Zhang et al., 2020; Salgotra and Chauhan 2023).

Disease Resistance

Hybridization in fish increases resistance to diseases, reducing the reliance on antibiotics and other chemical interventions. Recent research has shown that hybrid fish may be more resilient to common aquaculture related diseases, such as bacterial infections and parasites (Miranda et al., 2013). For instance, a study on hybrid grouper (*Epinephelus lanceolatus* × *E. coioides*) found that the hybrid offspring demonstrated significantly higher resistance to *Vibrio* spp. infections compared to their purebred counterparts (Sun et al., 2021). These results suggest that hybrid fish breeding could play a crucial role in minimizing the environmental impact of aquaculture by reducing the need for chemical interventions.

Despite these advantages, many questions about hybridization in aquatic animals remain unanswered. Why is biotechnology increasingly being applied in hybridization? What are the primary goals of hybridization, and what effects does it have on aquatic life? How do hybrid and genetically modified aquatic animals compare to their parent species in terms of resilience to environmental fluctuations? The answer lies in the numerous benefits of hybrid vigor (Ye et al., 2024). Hybrids are often characterized by faster growth, higher disease resistance, resilience under environmental stress, and improved antioxidant and immune capacity (Mitra et al., 2023; Franke et al., 2024). Due to their adaptability to fluctuating conditions, several species, such as zebrafish, have been introduced (Stickney et al., 2002; Zon & Peterson, 2005).

Previous studies have shown that zebrafish possess morphological and physiological traits that are remarkably like mammals, making them valuable in genomic research and pharmaceutical applications. Their adaptability and ability to perform large-scale phenotype-based screenings make them ideal for such purposes (Ton et al., 2002; Zon & Peterson, 2005). These characteristics are vital for producing high-quality offspring to meet the growing demand for food production. The desirable traits in hybrids encourage aquaculturists to increase hybrid production to address the shortage of aquatic life (Bartley et al., 2020). As a result, many new hybrid species have been introduced into aquaculture for human consumption (Olesen et al., 2003).

However, due to the unclear long-term effects of hybridization, many consumers prefer purebred fish over hybrids. Despite this, hybrids offer promising opportunities for high-quality production due to their rapid growth, high survival rates, and disease resistance (Krasnovyd et al., 2020; Bartley, 2021). Previous research indicates that hybrid populations can exhibit enhanced antioxidant and immune capacities, allowing them to better adapt to varying environmental conditions, such as salinity fluctuations (Ye et al., 2024).

Environmental Adaptability

Recent study has identified fish hybrids as a key factor with significant potential for resilience in fluctuating environments. These hybrids, which are often classified as genetically modified organisms (GMOs), possess a wide range of genetic variability, making them more resilient to ecological stressors such as ocean acidification (Jones et al., 2018; Sundin, 2023). Ocean acidification, which is on the rise, has a profound impact on aquatic life by altering the chemical composition of seawater and disrupting the physiological processes of many marine organisms (Sundin, 2023). This change disrupts normal metabolic functions and buffering capacities, thereby enhancing metabolic processes and increasing survival rates in certain species (Servili et al., 2023).

Some marine species exhibit a higher degree of resilience than others. For example, a previous study has shown that Atlantic salmon and brown salmon hybrids demonstrate greater adaptability to pH fluctuations compared to purebred species (Bryden et al., 2004). Similarly, Mustafa et al. (2013) found that hybrid groupers are more tolerant of ocean acidification than their purebred counterparts. These hybrids, therefore, display a greater capacity to adapt to climate change, exhibiting better endurance under stress compared to purebred species (Ye et al., 2024). Studies on hybrids in invertebrates have also reported better adaptability than purebreds (Salgotra and Chauhan 2023).

Water quality, which includes biological, chemical, and physical parameters, is crucial in aquaculture systems. Dissolved oxygen (DO) is a particularly vital component. Rapid depletion of DO can lead to hypoxia, which induces stress in fish, suppresses immunity, and can even result in death (Abdel-Tawwab et al., 2019). Research has shown that hypoxia can make fish more vulnerable to diseases (Moyson et al., 2015; Wang et al., 2023). However, Lee et al. (2024) observed that hybrid progenies exhibit higher survival rates compared to purebreds due to their superior ability to manage stress. Additionally, Roberts et al. (2010) discussed how hybrids could potentially replace obligately estuarine fish in nature. Therefore, cultivating hybrid species in controlled, closed-water systems is essential to harness their desirable traits and potential to replace natural species (Allendorf et al., 2001).

Economic Viability of Hybrid Fish

Hybrid fish offers numerous advantages, including higher survival rates, improved feed conversion ratios, enhanced adaptability to environmental conditions, greater disease resistance, faster growth rates, and significant cost reductions related to feed and disease management (Faudzi et al., 2017; Shapawi et al., 2018; Ahmed et al., 2019). Studies suggest that hybrid fish farming can be more profitable than purebred farming, especially regarding disease and feed management, due to hybrids' ability to thrive in fluctuating environments, which increases yields in aquaculture production. However, hybrid fish farming requires proper regulatory oversight, practical measures, and appropriate post-harvest handling to ensure sustainability and market success (Zhou & Gui, 2018). Innovations in aquaculture have further enhanced efficiency, with hybrid breeding providing economic benefits through improved productivity, higher market demand, disease resistance, and resource efficiency.

Hybrids often exhibit faster growth rates than their purebred counterparts. For example, a study on walleye and sauger hybrids demonstrated faster growth compared to purebreds, a trend seen in several other species as well (Giudice, 1966; Malison et al., 1990; Rosenfield et al., 2004; Nielsen et al., 2010). These growth advantages lead to higher productivity and yield in aquaculture. Additionally, hybrids tend to display greater disease resistance, as seen in hybrid chinook salmon, which showed improved resistance to diseases without significant differences in genetic diversity (Semple et al., 2021). Numerous studies support the observation that hybrids have superior disease resistance compared to purebreds (LaPatra et al., 1996; Bakke et al., 1999; Bunlipatanon & U-Taynapun, 2016; Šimková et al., 2022). This increased resilience, coupled with better feed conversion ratios, means hybrid fish require less feed, resulting in greater resource efficiency and lower costs related to disease management and feed.

Investing in hybrid fish breeding involves three main areas: initial investment, genetic management, and marketing. The initial investment includes breeding facility costs, training, and acquiring broodstock. Genetic management is essential to prevent negative impacts on native species and biodiversity, while marketing strategies ensure the commercial success of hybrids by considering consumer preferences and safety concerns. A comprehensive cost-benefit analysis is crucial for evaluating the feasibility of hybrid fish breeding, factoring in initial investments, operational costs, market prices, and other variables (Salgotra and Chauhan 2023).

Hybridization is a promising solution to address sustainability challenges in fisheries, particularly those caused by overfishing. Hybrids offer improved traits, such as faster growth, better disease resistance, and adaptability to environmental changes, which support market feasibility and help meet the growing demand for protein sources (Brown & Day, 2002). Global fish demand has increased, driven by population growth and consumer interest in healthy lifestyles, with a projected 1.5% annual rise in fish consumption through 2030 (FAO, 2020).

Consumers increasingly prefer hybrid products over purebreds because of their superior quality and sustainability. Market research indicates that consumers favor premium seafood products with high nutritional value and health benefits. For example, genetically improved tilapia has demonstrated better fatty acid metabolism, resulting in improved growth and nutritional quality (Ng & Hanim, 2007; Teoh et al., 2011). Hybrid tilapia have successfully penetrated global markets due to their taste, texture, and nutritional value, while hybrid catfish have gained popularity in the U.S. market, appreciated for their consistent quality and availability (Kumar et al., 2008; Stankus, 2010; Sun et al., 2022).

Hybridization contributes to the efficiency of fish farming by offering better growth rates, survival, and disease resistance compared to purebred species. These traits help reduce production costs and enhance profitability, supporting sustainable aquaculture practices (Dee et al., 2022). Genetically improved strains, such as hybrid tilapia, have demonstrated superior growth, survival, and adaptation to environmental stresses, making them a viable economic choice for aquaculture (Prabu et al., 2019; Zhao et al., 2020). Hybrids also exhibit greater resistance to diseases, reducing mortality rates and the need for antibiotics, further lowering costs related to disease and water management (Cai & Ma, 2004; Zabidi et al., 2021). Some examples of fish hybrids across fish family produced for aquaculture are summarized in Table 1.

Environmental and Ethical Considerations

Environmental Impacts

Releasing hybrid fish into natural environments may pose risks to native populations by introducing new competition for resources and causing genetic pollution (Alves et al., 2007; Laikre et al., 2010; Erarto & Getahub, 2020). Recent studies have raised concerns about the potential for hybrid fish to interbreed with native species, which could lead to the loss of unique genetic traits and disruption of local ecosystems (Arthington, 1991; Laikre et al., 2010; Bradbeer et al., 2019). However, advancements in technology, such as the development of sterile hybrids, have reduced the threat of genetic contamination, making fish breeding a more environmentally sustainable option (Bradbeer et al., 2019). These innovations highlight the importance of responsible breeding practices and the need for stringent regulations to safeguard natural ecosystems (Naish et al., 2007; Reid et al., 2018; Jolly et al., 2023).

Table 1: Summary of hybrid fish produced for the aquaculture industry

Family	Hybrid name	Parent species	Key traits	References
Moronidae	Hybrid Striped Bass	*Morone chrysops* ♀ × *Morone saxatilis* ♂	Hybrids exhibited higher growth rates but demonstrated lower survival at the lowest feeding level due to excessive cannibalism. Hybrids showed significantly lower metabolic energy expenditure and utilized food more efficiently than purebred. Showed higher growth efficiencies (12-15% higher), food conversion ratios. Hybrids exhibited lower metabolism (by 10-14%) and higher growth energy (by 10-14%)	Tuncer et al. (1990)
Ictaluridae	Hybrid catfish	Channel catfish, blue catfish, and their F1 and F2 Hybrids Use genus and species name consistently	F2 hybrid females had a significantly lower ovulation rate (12.2%) compared to channel catfish, blue catfish, and F1 hybrids (83.5, 58.4, and 56.5%, respectively). F2 hybrids produced fewer eggs per kilogram of body weight (923 eggs/kg) than the other groups (channel catfish: 7,893; blue catfish: 5,600; F1 hybrids: 5,676). F1 hybrids had smaller testes relative to body weight compared to channel catfish but not blue catfish. Fertilization rates were highest in channel catfish eggs (73.6%), while F3 hybrid eggs had much lower fertilization rates (5.1%). F1 hybrids rarely laid eggs when backcrossed to parent species, and F2 hybrids did not spawn naturally in various environments, indicating reproductive breakdown and difficulties in backcrossing.	Dunham & Argue (2020)
	Hybrid catfish	*Ictalurus punctatus* ♀ x *I. furcatus* ♂	At low densities, channel catfish fry grew faster than hybrid catfish fry. However, the hybrid catfish exhibited superior growth at higher densities, surpassing both channel and blue catfish in growth performance. Hybrid catfish demonstrated greater survival rates than channel catfish, particularly under conditions of stress such as oxygen depletion and bacterial infections.	Dunham et al. (1990)
		Ictalurus punctatus ♀ × *I. furcatus* ♂	F1 hybrids had higher growth rates, reaching an average weight of 666 grams compared to channel catfish (577 grams) and blue catfish (396 grams). Growth performance declined in later hybrid generations (F2, F3). F1 hybrids grew faster in high-density environment. backcross hybrids with parental species showed poorer growth performance.	Argue et al., (2014)
		Ictalurus punctatus ♀ × *I. furcatus* ♂	Hybrid Catfish demonstrated better growth performance compared to purebred. Survival rate higher for hybrids (75–97%) than purebred (67-94%). Hybrids reached higher harvest weight (671-825g) compared to purebred (525-821g)	Fantini-Hoag et al. (2022)
Portunidae	Hybrid mud crab	*S.olivacea* ♀ x *S. tranquebarica* ♂	The hybridization between *S. paramamosain* and S. tranquebarica resulted in fecundity ranging from 32,200 to 1,868,000 eggs, with a hatching rate between 2 and 45.8%. The hybridization of S. olivacea with S. tranquebarica resulted in a 98% hatching rate. Production of viable offspring (crablets) in interspecific hybridization is lower compared to intraspecific mating.	Gunarto et al. (2020)
Pleuronectidae	Hybrid yellowtail flounder	*Pleuronectes ferrugineus* ♀ x *Pleuronectes americanus* ♂	Despite the successful creation of hybrids, the gonad development in the hybrid fish was abnormal. Many hybrid individuals exhibited underdeveloped gonads or did not reach reproductive maturity, suggesting potential fertility issues with the hybrids. This could limit their ability to reproduce naturally in the wild or in aquaculture settings.	Park et al. (2003)
Acipenseridae	Hyrbid Sturgeon	*Acipenser Baerii* × *Acipenser gueldenstaedtii*	The survival rate of diploid hybrids was relatively high, with no significant difference compared to pure Siberian sturgeon. The mortality rate of triploid hybrids was approximately twice as high as that of diploid hybrids, indicating that triploidization negatively affected the viability of the hybrids.	Fopp-Bayat et al. (2022)
	Hybrid sturgeon	*Acipenser baerii* ♀ × *A. gueldenstaedtii* ♂	Excessive protein in the diet (beyond 400 g/kg) resulted in decreased growth, poorer protein utilization by the hybrids.	Guo et al. (2012)
Cyprinidae	Hybrid carp	female grass carp (*Ctenopharyngodon idella*) X male carp (*Cyprinus carpio*, Israeli mirrow variety)	Hybrid died during embryonic development	Stanley (2011)
	Hybrid grass carp	*Ctenopharyngodon idella* x *Hypophthalmichthys nobilis*	hybrid grass carp exhibited slow growth and high mortality rates. Hybrid grass carp consumed less vegetation and had a significantly lower feeding rate than grass carp. hybrids exhibited physical deformities such as spinal curvature, enlarged guts, and misshapen heads.	Osborne (2011)
	Hybrid carp	*Ctenopharyngodon idella* x *Aristichthys nobilis*	hybrid grass carp larvae exhibited very low survival rates (1-3%), despite achieving decent growth (84-212mg) over 13 days. The high mortality of hybrid larvae was attributed to genetic abnormalities resulting from hybridization.	Opuszynski et al. (1985)
	Hybrid carp	*Cyprinus carpio* X *Carassius gibelio*	The hybrids exhibited intermediate traits between the two parental species, both morphologically and physiologically. This included intermediate glucose and cholesterol levels, as well as an intermediate intestine-to-body size ratio, suggesting hybrid vigor in terms of food utilization, metabolism, and energy intake. hybrids demonstrated higher gonado-somatic indices (GSI) than common carp.	Šimková et al. (2015)
Cichlidae	Hybrid Nile Tilapia	*Oreochromis niloticus* x *O. mossambicus*)	The study observed that hybridization between male Nile tilapia and female Mozambique tilapia resulted in an all-female F1 generation.	Sarker et al. (2024)
	Hybrid Tilapia	*Oreochromis niloticus* x *Oreochromis mossambicus & Oreochromis mossambicus* x *Oreochromis niloticus*	Hybrids of *O. mossambicus* x *O. niloticus* showed positive heterosis on weight gain and biomass gain but low FCR. Hybrids of *O. niloticus* x *O. mossambicus* showed low spawning frequency. Hybrids superior for salinity. Potential for brackish water culture.	Kamal and Mair (2005)
Percidae	Hybrid walleye	*Stizostedion vitreum x S. canadense*	Hybrids had more severe erosion of pectoral and pelvic fins than walleyes. Hybrid more susceptible to columnaris disease caused by *Flexibacter columnaris*	Clayton et al. (1998)
Percidae	Hybrid walleye	*walleye ♀ × sauger S. canadense ♂*	Both walleyes and hybrids had high survival rates, with over 90% survival during the 126-day study. Hybrids grew faster than walleyes at lengths under 325mm, but walleyes reached the minimum market weight (681g) 31 days sooner than hybrids.	Siegwarth & Summerfelt (1993)

	Hybrid walleye	*walleyes* (*Stizostedion vitreum)* and *saugers (S. canadense*)	The W × S hybrids showed significantly greater weight gain, length gain, and condition factors compared to purebred walleyes and S × W hybrids. W × S hybrids exhibited less aggressive behavior and were less affected by routine disturbances and handling, making them easier to manage in an intensive culture setting. S × W hybrids had lower egg survival (48.0%).	Malison et al. (1990)
Pangasiidae	Hybrid catfish	*Pangasianodon hypophthalmus x Pangasius bocourti*	The hybrid fish exhibited significantly lower growth rates and survival compared to the parental species. Specific growth rate for hybrid was 0.60% compared to maternal (1.23%) and paternal (1.20%). Hybrids showed higher crude protein (74.74%) but lower lipid content (15.64%).	Hatachote et al. (2015)
Paralichthyidae	Hybrid flounder	*Platichthys stellatus x Kareius bicoloratus*	The hybrid larvae develop to a larger size and settle later than *P. stellatus*, but develop with a smaller size and settle earlier than the larvae *of K. bicoloratus*. Hybrids exhibit euryhaline characteristics similar to those of *P. stellatus*	Yamashita et al. (2014)
	Hybrid flounder	*Paralichthys olivaceus x P. dentatus*	hybrid flounder showed superior growth rates and temperature tolerance. Slow development of gastric digestion and earlier formation of pyloric ceca. the survival rates of hybrid flounder larvae through metamorphosis were low (approximately 30% compared to 70% in *P. olivaceus*).	Yu et al. (2010)
	Hybrid flounder	*Paralichthys olivaceus* x *P. dentatus*	no obvious heterosis during 64 days in the three crosses (Po x Pd, Fo x Po, Fo x Pd). the hybrids of Po x Pd demonstrated positive heterosis in growth and high temperature tolerance after 196dph.	Sui et al. (2013)
	Hybrid flounder	*Paralichthys olivaceus* x *Verasper variegatus*	Low percentage fertilization and hatching but high percentage of early survival.	Kim et al. (1996)
	Hybrid flounder	*Verasper variegatus Paralichthys olivaceus*	Low percentage of fertilization rate and no hatching	Kim et al. (1996)
Salmonidae	Hybrid salmon	*Salmo salar x Salmo trutta*	Hybrids between the two species displayed varying levels of susceptibility to *Gyrodactylus salaris* and *Gyrodactylus derjavini* based on the parental line, with resistance being influenced by the identity of the sire or dam.	Bakke et al. (1999)
	Hybrid salmon	marble trout (*Salmo marmoratus*) and the brown trout (*Salmo trutta*)	Hybrid offspring often showed better survival and growth rates than pure species, particularly in inter-specific competition. The hybrids were generally larger than both marble and brown trout in certain conditions, potentially indicating heterosis (hybrid vigor).	Meldgaarda et al. (2007)

Ethical Concerns

The ethical concerns surrounding fish hybridization breeding have raised significant attention among researchers, focusing on issues such as fish welfare, unintended consequences of genetic manipulation, and broader implications for natural ecosystems (Tiedje et al., 1989; Snow et al., 2005; Mastor et al., 2025). These concerns are particularly relevant with the increasing use of CRISPR and other gene-editing technologies in aquaculture, sparking debate among genetic engineers and conservationists about the potential for creating invasive species or disrupting natural food webs (Martin et al., 2010; Erarto & Getahun, 2020). Developing ethical guidelines and regulatory frameworks that balance the benefits of hybrid fish breeding with the need to protect animal welfare and biodiversity is essential (Ahmed et al., 2019; Cook et al., 2000).

Regulatory Frameworks

Table 2 illustrates that regulations governing hybrid fish breeding and aquaculture vary significantly across regions, with some enforcing strict controls on genetically modified organisms (GMOs) and hybrids. The growing complexity of international trade agreements and environmental standards has further complicated the regulatory landscape, as some countries have adopted more stringent rules regarding the import and export of such species (FAO, 2020). Consequently, it is crucial for consumers to maintain open communication with regulatory bodies to stay informed about these evolving regulations (Leng, 2020; McMahon, 2020).

Challenges and Limitations of Fish Hybridization

Genetic Instability

One of the main challenges in fish hybridization is maintaining genetic stability across successive generations. Recent studies have emphasized the risks of genetic drift and the potential loss of desirable traits in hybrid populations, particularly when hybrids are produced over multiple generations without proper management (Ahmed et al., 2019; Cook et al., 2000). To address this issue, comprehensive monitoring and breeding programs must be implemented to ensure genetic stability. These programs should incorporate genomic tools and marker-assisted selection (Kalueff et al., 2014; Coughlan et al., 2020). Such approaches help sustain desirable traits in hybrids, ensuring their reliable performance in commercial production settings (Bartley et al., 2020; Briggs, 2002).

Health and Welfare

Previous studies on fish hybridization have indicated that hybrid fish may be more susceptible to health issues, such as deformities or reduced fertility, which can negatively impact the efficiency of breeding programs (Krasnovyd et al., 2020; Bartley, 2021). The occurrence of deformities and other health problems is particularly common among hybrid offsprings, especially when raised under suboptimal conditions (Mitra et al., 2023; Franke et al., 2024). As a result, it is essential to closely monitor standard operating practices and breeding programs to ensure the production of high-quality hybrid progeny (Ye et al., 2024). This approach helps minimize health risks and improves the overall effectiveness of fish breeding efforts.

Regulatory and Public Perception

Obtaining regulatory approval for fish hybridization and securing public acceptance can be difficult, especially in areas where scepticism about GMOs and other forms of genetic modification exists. Recent surveys of public opinion revealed significant variability in consumer acceptance of hybrid fish products, with some expressing concerns over the safety and environmental impact of

Table 2: Regulatory frameworks for fish hybridization in various countries

Country/Region	Regulatory Body	Key regulations	Specific Guidelines for Hybridization	References
United States	U.S. Fish and Wildlife Service (USFWS)	National Environmental Policy Act (NEPA), Lacey Act, Endangered Species Act (ESA)	This act focusing on conservation of threatened and endangered plants and animals. Hybridization requires environmental assessments; restrictions on hybrid species that may impact native populations	National Aquaculture Act, 1980
European Union	European Commission (EC), Member States	Common Fisheries Policy (CFP), EU Habitats Directive	Focusing on sustainable management on fishing fleets and preserving fish stock. Hybrid species must comply with biodiversity and ecosystem protection guidelines; requires risk assessments	Council Directive 92/43/EEC
China	Ministry of Agriculture and Rural Affairs (MARA)	Fisheries Law of the People's Republic of China	The law is stipulate to enhance the protection, increasing and developing fishery resources. Strict regulations on the introduction and breeding of non-native species; licenses required for hybrid	Fisheries Law of the People's Republic of China, 1986
India	Ministry of Fisheries, Animal Husbandry and Dairying	Coastal Aquaculture Authority Act, 2005	This act encompasses the farming of aquatic life under controlled condition. Regulation of hybrid species in coastal aquaculture; guidelines for species introduction and environmental impact assessments	Coastal Aquaculture Authority Act, 2005
Japan	Ministry of Agriculture, Forestry and Fisheries (MAFF)	Fisheries Law of Japan	This act stipulates the basic framework of Japan's Fishery policy which hybridization activities require permits; environmental impact and biodiversity conservation are key considerations	Protection of Fisheries Resources Act, 1951
Norway	Directorate of Fisheries	Aquaculture Act, Nature Diversity Act	Hybridization must adhere to strict environmental and biodiversity conservation guidelines; licensing required. This act established a governing framework for aquaculture industry in inland and marine waters including the provincial sea, EEZ and mainland shelf of Norway	Aquaculture Act, 2005
Russia	Federal Agency for Fisheries (Rosrybolovstvo)	Federal Law on Fisheries and Conservation of Aquatic Biological Resources	Hybrid species breeding is strictly regulated; permits required, with a focus on conservation of native species. This law focusing on fisheries and conservation of aquatic biological resources which consisting of 65 articles	Federal Law, 2013
Vietnam	Ministry of Agriculture and Rural Development (MARD)	Fisheries Law of Vietnam	Regulations focus on preventing environmental degradation; hybridization must align with sustainable aquaculture practices. The law consists of two articles on 61 and 61 on illegal fishing which focusing on exploitation of fish	Law on Fisheries, 2019
South Africa	Department of Environment, Forestry and Fisheries (DEFF)	National Environmental Management Act (NEMA), Marine Living Resources Act	Hybridization requires environmental impact assessments; specific guidelines to protect native biodiversity. This act focusing on providing co-operative environmental governance by principal affecting the environment	Marine Living Resources Act, 1998
Brazil	Ministry of Agriculture, Livestock, and Supply (MAPA)	National Environmental Policy Act, Fisheries Law	Hybrid breeding must comply with environmental protection laws; specific regulations for non-native species but more focusing on protection of migratory fish	Sustainable Development Policy on Fisheries and Aquaculture, 2009
New Zealand	Ministry for Primary Industries (MPI)	Freshwater Fisheries Regulations 1983, Subclause (2) Part 8A Schedule 3	Focusing on indigenous species management. Prohibition of noxious fish species (Schedule 3) including its subspecies, hybrids and variations of the species	Fisheries Act, 1996
Australia	Department of Agriculture, Water and the Environment (DAWE)	Environment Protection and Biodiversity Conservation Act (EPBC Act)	Hybrid species must undergo rigorous risk assessments; regulations to prevent impacts on native species and ecosystems. Biodiversity conservation refers to the protection, preservation, and management of ecosystems and natural habitats and ensuring that they are healthy and functional. To protect and preserve species diversity. To ensure sustainable management of the species and ecosystems.	EPBC Act, 1999
Canada	Fisheries and Oceans Canada (DFO)	Fisheries Act, Species at Risk Act (SARA)	Focusing on four categories which are endangered, threated, extirpated and special concern. Hybridization practices are regulated to protect native species; permits required for hybrid breeding activities. Section 73 of the Species at Risk Act ('SARA', the Act) sets out conditions that must be met before a competent minister can issue a permit for an activity affecting a listed wildlife species, any part of its critical habitat or the residences of its individuals.	Fisheries Act, 1985
Thailand	Department of Fisheries (DOF)	Fisheries Act of Thailand	Hybridization is regulated with a focus on preventing adverse environmental impacts and protecting native species. This Act lays down the general principles relating to fisheries. The 104 Sections of the Act are divided into a title part (sections 1 to 5) and 11 Chapters: Fisheries Management (1); Fishery Zone (2); Promotion of Aquaculture (3); Standard of Fish or Fish Products (4); Importation and Exportation of Fish and Fish Products (5); Overseas Marine Fishery (6); Fees on license or Permit and Substitute (7); Transferability (8); Competent Official (9); Administrative Measure (10); Penalties (11).	Fisheries Act, 1947

South Korea	Ministry of Oceans and Fisheries (MOF)	Fisheries Act, Environmental Impact Assessment Act	Strict guidelines for hybrid species; environmental impact assessments are mandatory before breeding. The purpose of this Act is to promote environment-friendly, sustainable development and healthy and pleasant life of citizens by forecasting and assessing the environmental impacts of a plan or project and by formulating measures for environmental conservation when a plan or project that has an environmental impact is formulated and implemented.	Environmental Impact Assessment Act, 1
Malaysia	Fisheries Department Malaysia	Fisheries Act 1985 Section 40(2) Please refer to the Malaysian Biosafety Law (Akta 678) which mentions crossing of species beyond their natural reproductive range.	No specific regulations for fish hybridization but Part VIII, section 40 (2) of the Fisheries Act 1985 on control the release of non-indigenous fish species into the natural environment may govern this activity in Malaysia.	Fisheries Act (No. 317 of 1985) 1985

genetically modified or hybridized fish (Pérez-Ramírez et al., 2020; Dayé et al., 2023). To address these challenges, the aquaculture industry needs to prioritize transparent communication and public education, emphasizing the benefits of hybrid fish while addressing concerns related to its safety and sustainability (Love et al., 2021).

Future Directions and Innovations in Fish Hybridization

The future of fish hybridization is poised for significant advancements through the integration of cutting-edge genomic technologies such as CRISPR and other gene-editing techniques (Charpentier, 2017; Yoon et al., 2023) which offer precise genetic modifications to enhance traits like disease resistance, environmental adaptability, improved growth rates, and higher survival rates (Snow et al., 2005; Ahmed et al., 2019; Cook et al., 2000). Despite these advancements, ethical and regulatory concerns surrounding gene-editing in aquaculture must be properly addressed. Alongside these technologies, selective breeding programs that leverage genomic selection and marker-assisted breeding are becoming increasingly important, enabling the accurate identification of desirable traits and improving breeding outcomes (Gjedrem et al., 2020; Lal et al., 2024). As climate change continues to impact ecosystems, hybrid species such as tilapia and catfish are being developed to adapt to shifting environmental conditions, including changes in water temperature and salinity, ensuring the sustainability of global seafood production (Free et al., 2019). Furthermore, incorporating fish hybridization into sustainable aquaculture practices, such as multi-trophic systems and recirculating aquaculture systems (RAS), can significantly boost efficiency and reduce environmental impact, contributing to the long-term preservation of aquatic ecosystems (Troell et al., 2020; Salgotra and Chauhan 2023; Lal et al., 2024).

Conclusion

Fish hybridization offers a promising strategy for enhancing the productivity, resilience, and sustainability of aquaculture. By combining favourable traits from different species or strains, hybrid fish can deliver significant advantages, such as faster growth rates, improved disease resistance, and greater adaptability to environmental changes. Advances in genomic technologies, selective breeding, and sustainable farming practices have further amplified the potential of hybrid fish to contribute to global seafood security. However, the success of these breeding programs depends on careful management, comprehensive research, and responsible practices to address the potential risks and challenges associated with hybridization. As global seafood demand continues to rise, hybrid fish breeding is expected to play an increasingly crucial role in ensuring seafood security and fostering the development of sustainable aquaculture.

DECLARATIONS

Funding: The preparation of this review article was funded by the Higher Institution Centre of Excellence (HICoE) Research Funding (No. JPT(BKPI)1000/016/018/35(2), Grant Code HIC2401), provided by the Ministry of Higer Education, Malaysia.

Acknowledgement: The authors gratefully acknowledge the support of Universiti Malaysia Sabah (UMS) for providing access to reference search facilities and for funding the Article Processing Charges (APC). The authors also acknowledge the Ministry of Higher Education, Malaysia for the provision of research funding.

Conflict of Interest: The authors declare that they have no conflict of interest.

Data Availability: The authors do not have permission to share data.

Competing Interest: The authors declare that there are no competing financial interests or personal relationships that could influence the work reported in this article.

Ethics Statement: This study did not involve the use of human participants or animal samples. The article is original and free from plagiarism. The article, in whole or in part, has not been published elsewhere and is not under consideration by any other journal. The authors affirm that they have adhered to professional ethical standards in the preparation and publication of this work.

Author's Contribution: WNFSWN prepare the initial manuscript draft; NNIM, NHZ, NMF and KFR critical reviewed and refined the draft; JR conceived the study, carried out the final editorial revisions and oversaw the manuscript's submission.

Generative AI Statement: The authors declare that no

Gen AI/DeepSeek was used in the writing/creation of this manuscript.

Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

Ababouch, L., Nguyen, K.A.T., Souza, M.C.,D., and Fernandez-Polanco, J. (2023). Value chains and market access for aquaculture products. *Journal of the World Aquaculture Society*, 54(2), 527-553. https://doi.org/10.1111/jwas.12964

Abdel-Tawwab, M., Monier, M., Hoseinifar, S.H., and Faggio, C. (2019). Fish response to hypoxia stress: growth, physiological, and immunological biomarkers. *Fish Physiology and Biochemistry,* 45, 997-1013. https://doi.org/ 10.1007/s10695-019-00614-9

Abwao, J., Jung'a, J., Barasa, J.E., Kyule, D., Opiyo, M., Awuor, J.F., Ogello, E., Munguti, J.M., and Keya, G.A., (2021). Selective breeding of Nile tilapia, *Oreochromis niloticus*: A strategy for increased genetic diversity and sustainable development of aquaculture in Kenya. *Journal of Applied Aquaculture*, 35 (2), 237-256. https://doi.org/10.1080/10454438.2021.1958728

Adah, P.M., Onyia, L., and Obande, R.A. (2014). Fish hybridization in some catfishes: A review. *Biotechnology*, 13(6), 248-251. https://doi.org/10.3923/BIOTECH.2014.248.251

Ahmed, N., Thompson, S., and Glaser, M. (2019). Global Aquaculture productivity, environmental sustainability, and climate change adaptability. *Environmental Management,* 63(2), 159-172. https://doi.org/10.1007/s00267-018-1117-3

Albouy, C., Velez, L., Coll, M., Colloca, F., Loc'h, F., Mouillot, D., and Gravel, D. (2014). From projected species distribution to food-web structure under climate change. *Global Change Biology*, 20(3), 730–741. https://doi.org/10.1111/gcb.12467

Allendorf, F.W., Leary, R.F., Spruell, P., and Wenburg, J.K. (2001). The problems with hybrids: setting conservation guidelines. *Trends in Ecology & Evolution,* 16(11), 613-622.https://doi.org/10.1016/S0169-5347(01)02290-X

Alm, G. (1955). Artificial hybridization between different species of the salmon family. Fishery Board Report of Sweden, Institute of Freshwater Research Report No. 36 pp.13-56

Alves, C.B.M., Vieira, F., Magalhães, A.L.B., and Brito, M.F.G. (2007). Impacts of non-native fish species in Minas Gerais, Brazil: Present situation and prospects. In T.M. Bert, (Ed.), *Ecological and genetic implications of aquaculture activities: Methods and technologies in fish biology and fisheries* (vol. 6., pp.291-314). Springer. https://doi.org/10.1007/978-1-4020-6148-6_16

Aquaculture Act 2005 (No. 79). Norwegian Ministry of Fisheries and Coastal Affairs.

Argue, B.J., Kuhlers, D.L., Liu, Z., and Dunham, R.A. (2014). Growth of channel catfish (*Ictalurus punctatus*), blue catfish (*I. furcatus*), and their F1, F2, F3, and F1 reciprocal backcross hybrids in earthen ponds. *Journal of Animal Science*, 92(10), 4297-4305. https://doi.org/10.1016/S0044-8486(03)00216-3

Arthington, A.H. (1991). Ecological and genetic impacts of introduced and translocated freshwater fishes in Australia. *Canadian Journal of Fisheries and Aquatic Sciences*, 48(S1). https://doi.org/10.1139/f91-302

Bakke, T.A., Soleng, A., and Harris, P.D. (1999). The susceptibility of Atlantic salmon (*Salmo salar* L.)×brown trout (*Salmo trutta* L.) hybrids to *Gyrodactylus salaris* Malmberg and *Gyrodactylus derjavini* Mikailov. *Parasitology*, 119(5), 467-481. https://doi.org/10.1017/S0031182099004990

Bartley, D.M. (2021). GIFT transfer risk management: Genetics. Genetic risk analysis and recommended risk management plan for the transfer of GIFT (*Oreochromis niloticus*) from Malaysia to Nigeria. Penang, Malaysia: WorldFish. Program Report: 2021-12.

Bartley, D.M., Rana, K., and Immink, A.J. (2020). The use of inter-specific hybrids in aquaculture and fisheries. *Reviews in Fish Biology and Fisheries*, 30(3), 325-337. https://doi.org/10.1023/A:1016691725361

Bastardie, F., Salvany, L., Cooper, A.M., and Carvalho, N. (2024). A roadmap to reduce the risk of overexploiting EU marine living resources in a changing ocean. *Frontiers in Marine Science*, *11*, 1352500. https://doi.org/10.3389/fmars.2024.1352500

Beaugrand, G., Edwards, M., and Legendre, L. (2010). Marine biodiversity, ecosystem functioning, and carbon cycles. *Proceedings of the National Academy of Sciences*, 107(22), 10120–10124. https://doi.org/10.1073/pnas.0913855107

Beveridge, M.C.M., Phillips, M.J., and Clarke, R.M. (2018). A quantitative and qualitative assessment of wastes from aquatic animal production. In D. J. Baird, M. C. M. Beveridge, L. A. Kelly, & J. F. Muir (Eds.), Aquaculture and Water Resource Management (pp. 5-39). Blackwell Science

Blanc, J.M., and Chevassus, B. (1979). Interspecific hybridization of salmonid fish. I. Hatching and survival up to the 15th day after hatching in F, generation hybrids. *Aquaculture*, 18 (1), 21-34. https://doi.org/10.7717/peerj.16717

Bradbeer, S.J., Harrington, J., Watson, H., Warraich, A., Shechonge, A., Smith, A., Tamatamah, R., Ngatunga, B.P., Turner, G.F., and Genner, M.J. (2019). Limited hybridization between introduced and critically endangered indigenous tilapia fishes in Northern Tanzania. *Hydrobiologia*, 832, 257-268. https://doi.org/10.1007/s10750-018-3572-5

Briggs, J.P. (2002). The Zebrafish: A new model organism for integrative physiology. *American Journal of Physiology, Regulatory, Integrative and Comparative Physiology,* 282(1), R3-R9. https://doi.org/10.3103/S009545271806004X

Brown, C., and Day, R.L. (2002). The future of stock enhancements: lessons for hatchery practice from conservation biology. *Fish and Fisheries*, *3*(2), 79–94. https://doi.org/10.1046/J.1467-2979.2002.00077.X

Bryden, C.A., Heath, J.W., and Heath, D.D. (2004). Performance and heterosis in farmed and wild Chinook salmon (*Oncorhynchus tshawytscha*) hybrid and purebred crosses. *Aquaculture, 235(1-4), 249–261.* https://doi.org/10.1016/j.aquaculture.2004.01.027

Bunlipatanon, P., and U-Taynapun (2016). Growth performance and disease resistance against *Vibrio vulnificus* infection of novel hybrid grouper (*Epinephelus lanceolatus* × *Epinephelus fuscoguttatus*). *Aquaculture Research*, 48(4), 1711-1723. https://doi.org/10.3389/fvets.2021.675962

Cai, W., and Ma, J. (2004). Diseases resistance of Nile tilapia (*Oreochromis niloticus*), blue tilapia (*Oreochromis aureus*) and their hybrid (female Nile tilapia×male blue tilapia) to *Aeromonas sobria*. *Aquaculture*, 229(1-4), 79-87. https://doi.org/10.1016/S0044-8486(03)00357-0

Cao, L., Chen, P., Hou, X., Jun Ma, J., Ning Yang, N., Yanping Xu, Y., Yanjin Zhang, Y., Anqi Zhao, A., Jiyuan Zhang, J., Xinyu Li, X., and Hai Huang, H. (2022). Genetic characteristics and growth patterns of the hybrid grouper derived from the hybridization of *Epinephelus fuscoguttatus* (female) × *Epinephelus polyphekadion* (male). *Journal of Fish Biology*, 102, 328-339. https://doi.org/10.1111/jfb.15263

Ch'ng, C.L., and Senoo, S. (2008). Egg and larval development of a new hybrid grouper, tiger grouper *Epinephelus fuscoguttatus* × giant grouper *E. lanceolatus*. *Aquaculture Science*, 56(4), 505-512. https://doi.org/10.11233/aquaculturesci.56.505

Charpentier, E. (2017). Gene editing and genome engineering with CRISPR-Cas9. *Advances in Biochemical Engineering/Biotechnology*, 165, 55-72. https://doi.org/10.1142/S2529732517400119

Cheung, W.W., Pauly, D., and Sumaila, U.R. (2025). Hope or despair revisited: assessing progress and new challenges in global fisheries. *Fish and Fisheries*, *26*(2), 257-269. https://doi.org/10.1111/faf.12877

Chevassus, B. (1979). Hybridization in salmonids: results and perspectives. *Aquaculture*, 17, 113-128. https://doi.org/10.1016/0044-8486(79)90047-4

Chiquito-Contreras, R.G., Hernández-Adame, L., Alvarado-Castillo, G., Martínez-Hernández, M., Sánchez-Viveros, G., and Hernández-Montiel, L. (2022). Aquaculture—production system and waste management for agriculture fertilization—A review. *Sustainability*, 14(12), 7257. https://doi.org/10.3390/su14127257

Clayton, R.D., Stevenson, T.L. and Summerfelt, R.C. (1998). Fin erosion in intensively cultured walleyes and hybrid walleyes. *The Progressive Fish-Culturist*, 60(2): 114-118. https://doi.org/10.1577/1548-8640(1998)060<0114:FEIICW>2.0.CO;2

Coastal Aquaculture Authority Act 2005 (No. 24, Chapter 11), India Code, New Dehli, India.

Coll, M., Libralato, S., Tudela, S., Palomera, I., and Pranovi, F. (2008). Ecosystem overfishing in the ocean. *PLoS ONE*, 3(12), e3881. https://doi.org/10.1371/journal.pone.0003881

Cook, J.T., McNiven, M.A., Richardson, G.F., and Sutterlin, A.M. (2000). Growth rate, body composition and feed digestibility/conversion of growth-enhanced transgenic Atlantic salmon (*Salmo salar*). *Aquaculture,* 188 (1-2), 15-32. https://doi.org/10.1016/S0044-

8486(00)00331-8
Coughlan, J.M., Brown, M.W., and Willis, J.H. (2020). Patterns of hybrid seed inviability in the *Mimulus guttatus* sp. complex reveal a potential role of parental conflict in reproductive isolation. *Current Biology*, *30*(1), 83-93 https://doi.org/10.1016/j.cub.2019.11.023
Day, F. (1882). On hybrids between salmon and trout. *Proceedings of the Zoological Society of London*, 751-753. https://doi.org/10.1111/j.1096-3642.1883.tb02790.x
Dayé, C., Spök, A., Allan, A.C., Yamaguchi, T., and Sprink, T. (2023). Social acceptability of cisgenic plants: public perception, consumer preferences, and legal regulation. In *Cisgenic crops: Safety, legal and social issues* (pp. 43-75). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-10721-4_3
Dee, M.M., Leungnaruemitchai, A., Suebsong, W., Somjai, D., Nimnual, K., Abdurahman, L., and Nganing K. (2022). A comparative growth performance and survival of different genetic strains of Nile tilapia (*Oreochromis niloticus*) and red tilapia (*Oreochromis* spp) in a floating net cage culture farming in the Cirata Lake, West Java Indonesia. *Thai Journal of Agricultural Science*, 54(4), 280-293.
Devlin, R.H., Sundstrom, L.F., and Leggatt, R.A. (2015). Assessing ecological and evolutionary consequences of growth-accelerated genetically engineered fishes. *BioScience,* 65, 685-700. https://doi.org/10.1093/biosci/biv068
du Pontavice, H., Gascuel, D., Reygondeau, G., Maureaud, A., and Cheung, W.W.L. (2019). Climate change undermines the global functioning of marine food webs. *Global Change Biology*, 26(3), 1306–1323. https://doi.org/10.1111/gcb.14944
Dunham, R.A., and Argue, B.J. (2000). Reproduction among channel catfish, blue catfish, and their F1 and F2 hybrids. *Transactions of the American Fisheries Society*, 129(1), 222-231. https://doi.org/10.1577/1548-8659(2000)129<0222:RACCBC>2.0.CO;2
Dunham, R.A., Brummett, R.E., Ella, M.O., and Smitherman, R.O. (1990). Genotype-environment interactions for growth of blue, channel and hybrid catfish in ponds and cages at varying densities. *Aquaculture,* 85(1-4), 143-151. https://doi.org/10.1016/0044-8486(90)90013-D
Dunham, R.A., Ely, B., and Liu, Z. (2020). Catfish hybridization: An overview. *Aquaculture Reports*, 17, 100394. https://doi.org/10.3923/biotech.2014.248.251
El-Sayed, A.-F.M., and Kawanna, M. (2021). Recent advances in tilapia aquaculture. *Aquaculture International*, 29(4), 1101-1118. https://doi.org/10.1007/s10499-021-00692-6
Environmental Impact Assessment Act, No. 1. (South Korea). (1993). Retrieved from https://elaw.org/wpcontent/uploads/archive/30_environmental_impact_assessment_system%20(1).pdf
EPBC Act (1999). Environment protection and biodiversity conservation act 1999. Canberra: comlaw. gov. au
Erarto, F., and Getahun, A. (2020). Impacts of introductions of alien species with emphasis on fishes. *Internation Journal of Fisheries and Aquatic Studies*, 8(5), 207-216.
Fantini-Hoag, L., Hanson, T., Kubitza, F., Povh, J.A., Filho, R.A.C. C., and Chappell, J. (2022). Growth performance and economic analysis of hybrid catfish (channel catfish *Ictalurus punctatus* ♀ × blue catfish, *I. furcatus* ♂) and channel catfish (*I. punctatus*) produced in floating in-pond raceway system. *Aquaculture Reports*, 23, 101065. FAO (2020). The State of World Fisheries and Aquaculture 2020: Sustainability in action. Food and Agriculture Organization of the United Nations
FAO. (2022). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO. https://doi.org/10.4060/cc0461en
Faudzi, N.M., Yong, A.S.K., Shapawi, R., Senoo, S., Biswas, A., and Takii, K. (2017). Soy protein concentrate as an alternative in replacement of fish meal in the feeds of hybrid grouper, brown-marbled grouper (*Epinephelus fuscoguttatus*) × giant grouper (*E. lanceolatus*) juvenile. *Aquaculture Research,* 49,421-441. https://doi.org/10.1111/are.13474
Federal Law, 2013 (No. 148-FZ) on Aquaculture (Fish farming). Constitution of the Russian Federation.
Fisheries Act, 1996 (No 88 of 1996). New Zealand Legislation.
Fisheries Act, B.E. 2490 (1947). (Thailand). Retrieved from https://faolex.fao.org/docs/pdf/tha4931.pdf
Fisheries Act. R. S. C. (1985). c. F-14. 2019. https://bit.ly/2wlqKPV
Fisheries Law of the People's Republic of China. (1986). Order No. 34 of the President, adopted January 20, 1986, effective July 1, 1986; amended 2013. Standing Committee of the National People's Congress of the PRC. https://www.chinajusticeobserver.com/law/x/fisheries%20law-20131228
Flourizel, I., Akpevwe, O.E., and Osijaye, G.K. (2023). Aquaculture advancement in biotechnology: Review. *International Journal for Research in Agricultural and Food Science*, 9(2), 22-37. https://doi.org/10.53555//gafs.v9i2.2237
Fopp-Bayat, D., Tomasz Ciemniewski, T., and Cejko, B.I. (2022). Embryonic development and survival of Siberian sturgeon × Russian sturgeon (*Acipenser baerii* × *Acipenser gueldenstaedtii*) hybrids cultured in a RAS system. *Animals*, 13(1), 42. https://doi.org/10.3390/ani13010042
Franke, A., Beemelmann, A., and Miest, J.J., (2024). Are fish immunocompetent enough to face climate change? *Biology Letter,* 20(2), 20230346. https://doi.org/10.1098/rsbl.2023.0346
Free, C.M., Thorson, J.T., Pinsky, M.L., Oken, K.L., Wiedenmann, J., and Jensen, O.P. (2019). Impacts of historical warming on marine fisheries production. *Science*, 363(6430), 979-983. https://doi.org/10.1126/science.aau1758
Giudice, J.J., (1966). Growth of a blue X channel catfish hybrid as compared to its parent species. *The Progressive Fish-Culturist*, 28 (3), 142-145. https://doi.org/10.1577/1548-8640(1966)28[142:GOABXC]2.0.CO;2
Gjedrem, T., Robinson, N., and Rye, M. (2020). The importance of selective breeding in aquaculture to meet future demands for animal protein: A review. *Aquaculture*, 519, 734875. https://doi.org/10.1016/j.aquaculture.2012.04.008
Gladju, J., Kamalam, B.S., and Kanagaraj, A. (2022). Applications of data mining and machine learning framework in aquaculture and fisheries: A review. *Smart Agriculture Technology*, 2, 100061. https://doi.org/10.1016/j.atech.2022.100061
Green, J.R. (1881). Hybridizing fishes. *Transactions of the American Fisheries Society*, 10 (1), 5-34. https://doi.org/10.1577/1548-8659(1881)11[5:HF]2.0.CO;2
Gunarto, Sulaeman, and Herlinah (2020). The mating success and hybridization of mud crab, *Scylla* spp. in controlled tanks. *AACL Bioflux*, 13(1), 428-438.
Guo, Z., Zhu, X., Liu, J., Han, D., Yang, Y., Lan, Z., and Xie, S. (2012). Effects of dietary protein level on growth performance, nitrogen and energy budget of juvenile hybrid sturgeon, *Acipenser baerii* ♀× *A. gueldenstaedtii* ♂. *Aquaculture*, 338, 89-95. https://doi.org/10.1016/j.aquaculture.2012.01.008
Harbicht, A., Wilson, C.C., and Fraser, D.J. (2014). Does human-induced hybridization have long-term genetic effects? Empirical testing with domesticated, wild and hybridized fish populations. *Evolutionary Applications*, 7(10), 1180-1191. https://doi.org/10.1111/eva.12199
Hatachote, S., Sriphairoj, K., and Na-Nakorn, U. (2015). Growth and flesh quality of the hybrid between *Pangasianodon hypophthalmus* and *Pangasius bocourti. Kasetsart Journal of Natural Sciences,* 49, 717-725.
Hilborn, R., Branch, T.A., Ernst, B., Magnusson, A., Minte-Vera, C.V., Scheuerell, M.D., and Valero, J.L. (2003). State of world fisheries. *Annual Review of Environmental and Resources*, 28(1), 359-399. https://doi.org/10.1146/annurev.energy.28.050302.105509
Hodapp, D., Roca, I.T., Fiorentino, D., Garilao, C., Kaschner, K., Kesner-Reyes, K., Schneider, B., Segschneider, J., Kocsis, Á.T., Kiessling, W., Brey, T., and Froese, R. (2023). Climate change disrupts core habitats of marine species. *Global Change Biology*, 29(2), 421–434. https://doi.org/10.1111/gcb.16612
Hoffmann, A.A., Miller, A.D., and Weeks, A.R. (2021). Genetic mixing for population management: From genetic rescue to provenancing. *Evolutionary Applications*, *14*(3), 634-652. https://doi.org/10.1111/eva.13154
Hossain, A., Habibullah-Al-Mamun, M., Nagano, I., Masunaga, S., Kitazawa, D., and Matsuda, H. (2022). Antibiotics, antibiotic-resistant bacteria, and resistance genes in aquaculture: risks, current concern, and future thinking. *Environmental Science and Pollution Research*, 1-22. https://doi.org/10.1007/s11356-021-17825-4
Hubbs, C.L. (1955). Hybridization between fish species in nature. *Systematic Zoology,* 4(1), 1-20. https://doi.org/10.2307/sysbio/4.1.1
Jolly, C.M., Nyandat, B., Yang, Z., Ridler, N., Matias, F., Zhang, Z., Murekezi, P., and Menezes, A. (2023). Dynamics of aquaculture governance. *Journal of the World Aquaculture Society*, 54(2), 427-481. https://doi.org/10.1111/jwas.12967
Jones, J.M., Passow, U., and Fradkin, S.C. (2018). Characterizing the vulnerability of intertidal organisms in Olympic National Park to ocean acidification. *Elementa: Science of the Anthropocene,* 6, 54. https://doi.org/10.1525/elementa.312
Kalueff, A.V., Stewart, A.M., and Gerlai, R. (2014). Zebrafish as an emerging model for studying complex brain disorders. *Trends in Pharmacological Sciences*, 35(2), 63-75. https://doi.org/10.1016/j.tips.2013.12.002
Kamal, A.H.M.M., and Mair, G.C. (2005). Salinity tolerance in superior genotypes of tilapia, *Oreochromis niloticus*, *Oreochromis mossambicus* and their hybrids. *Aquaculture*, 247(1–4), 189–201. https://doi.org/10.1016/J.AQUACULTURE.2005.02.008

Kelling, I., Carrigan, M., and Johnson, A.F. (2023). Transforming the seafood supply system: challenges and strategies for resilience. *Food Security*, *15*(6), 1585-1591. https://doi.org/10.1007/s12571-023-01400-5

Kim, K-K., Bang, I.C., Kim, Y., Nam, Y.K., and Kim, D.S. (1996). Early survival and chromosomes of intergeneric hybrids between Japanese flounder *Paralichthys olivaceus* and spotted halibut *Verasper variegatus*. *Fisheries Science*, 62(3), 490-491. https://doi.org/10.2331/fishsci.62.490

Krasnovyd, V., Vetešník, L., and Šimková, A. (2020). Distribution of host-specific parasites in hybrids of phylogenetically related fish: the effects of genotype frequency and maternal ancestry?. *Parasites and Vectors*, *13*, 1-11. https://doi.org/10.1186/s13071-020-04271-3

Kumar, G., Quagrainie, K., and Engle, C. (2008). Factors that influence frequency of purchase of catfish by U.S. households in selected cities. *Aquaculture Economics & Management*, 12(4), 299-314. https://doi.org/10.1080/13657300802494297

Laikre, L., Schwartz, M.K., Waples, R.S., Ryman, N., and Group, T.G.W. (2010). Compromising genetic diversity in the wild: Unmonitored large-scale release of plants and animals. *Trends in Ecology and Evolution,* 25(9), 520-529. https://doi.org/10.1016/j.tree.2010.06.013

Lal, J., Vaishnav, A., Singh, S.K., Meena, D.K., Biswas, P., Mehta, N.K., Priyadarshini, M.B. (2024). Biotechnological innovation in fish breeding: from marker assisted selection to genetic modification. *Discover Biotechnology*, 1:7. https://doi.org/10.1007/s44340-024-00007-6

LaPatra, S.E., Lauda, K.A., Jones, G.R., Shewmaker, W.D., Groff, J.M., and Routledge, D. (1996). Susceptibility and humoral response of brown trout X lake trout hybrids to infectious hematopoietic necrosis virus: a model for examining disease resistance mechanisms. *Aquaculture*, 146(3-4), 179-188. https://doi.org/10.1016/S0044-8486(96)01381-6

Law on Fisheries, 2019 (18/2017/QH14). Constitution of the Socialist Republic of Vietnam.

Lee, J., Han, K.H., Choi, W.S., Yu, T.S., Kim, H.S., and Lee, S.H. (2024). Effects of water temperature and salinity on the growth and survival of hybrid pufferfish larvae (*Takifugu obscurus*♀ x *T. rubripes*♂). *Aquaculture Research,* 2024, 511980. https://doi.org/10.1155/2024/8511980

Leng, S. (2020). Consumer awareness and acceptance of aquaculture practices and products in Penang, Malaysia. *European Proceedings of Social and Behavioural Sciences*, 98, 629-637. https://doi.org/10.15405/epsbs.2020.10.02.68

Leung, T.L.F., and Bates, A.E. (2013). More rapid and severe disease outbreaks for aquaculture at the tropics: implications for food security. *Journal of Applied Ecology*, *50*(1), 215–222. https://doi.org/10.1111/1365-2644.12017

Lorenzen, K., Beveridge, C.M., and Mangel, M. (2012). Cultured fish: integrative biology and management of domestication and interactions with wild fish. *Biological Reviews,* 87, 639-660. https://doi.org/10.1111/j.1469-185X.2011.00215.x

Love, D.C., Allison, E.H., Asche, F., Belton, B., Cottrell, R.S., Froehlich, H.E., Gephart, J.A., Hick, C.C., Little, D.C., Nussbaumer, E.M., da Silva, P.P., Poulain, F., Rubio, A., Stoll, J.S., Tlusty, M.F., Thorne-Lyman, A.L., Troell, M., and Zhang, W. (2021). Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. *Global Food Security*, 28, 100494. https://doi.org/10.1016/j.gfs.2021.100494

Lu, C.L., Chen, S.N., and Hung, S. (2019). Application of novel technology in aquaculture. In Q. Lu & M. Serajuddin, (Eds.), Emerging Technologies, Environment and Research for Sustainable Aquaculture. *IntechOpen*. https://doi.org/10.5772/intechopen.90142

Lu, J., Fang, W., Huang, J., and Li, S. (2021). The application of genome editing technology in fish. *Marine Life Science and Technology*, 3, 326-346. https://doi.org/10.1007/s42995-021-00091-1

Lu, M., Zhang, Q.C., Zhu, Z. Y., Peng, F., Li, Z., Wang, Y., Li, X., Wang, Z., Zhang, X., Zhou, L., and Gui, J. F. (2023). An efficient approach to synthesize sterile allopolyploids through the combined reproduction mode of ameiotic oogenesis and sperm-egg fusion in the polyploid Carassius complex. *Science Bulletin*, *68*(10), 1038-1050. https://doi.org/10.1016/j.scib.2023.04.029

Luo, W., Zeng, C., Yi, S., Robinson, N., Wang, W., and Gao, Z. (2014). Heterosis and combining ability evaluation for growth traits of blunt snout bream (*Megalobrama amblycephala*). *Marine and Freshwater Biology*, 59, 857-864. https://doi.org/10.1007/s11434-014-0115-y

Malison, J.A., Kayes, T.B., Held, J.A., and Amundson, C.H. (1990). Comparative survival, growth, and reproductive development of juvenile walleye and sauger and their hybrids reared under intensive culture conditions. *The Progressive Fish Culturist*, 52(2), 73-82. https://doi.org/10.1577/1548-8640(1990)052<0073:CSGARD>2.3.CO;2

Manan, H., Jalilah, M., Fauzan, F., Ikhwanuddin, M., Amin-Safwan, A., Abdullah, N.S., Nur-Syahirah, M., and Kasan, N. (2023). Recent developments in aquaculture – A review. *Annals of Animal Science,* 23(2), 1-16. https://doi.org/10.2478/aoas-2023-0044

Mangano, M.C., Berlino, M., Corbari, L., Milisenda, G., Lucchese, M., Terzo, S., Bosch-Belmar, M., Azaza, M.S., Babarro, J.M.F., Bakiu, R., Broitman, B. R., Buschmann, A.H., Christofoletti, R., Dong, Y., Glamuzina, B., Luthman, O., Makridis, P., Nogueira, A. J. A., Paloma, M.G., Dineshram, R., and Sarà, G. (2022). The aquaculture supply chain in the time of covid-19 pandemic: Vulnerability, resilience, solutions and priorities at the global scale. *Environmental Science & Policy*, *127*, 98-110. https://doi.org/10.1016/j.envsci.2021.10.014

Marine Living Resources Act, 1998 (No. 107). Constitution of the Republic of South Africa.

Martin, C.W., Valentine, M.M., and Valentine, J.F. (2010). Competitive interactions between invasive Nile tilapia and native fish: The potential for altered trophic exchange and modification of food webs. *PloSOne*, 5(12), e14395. https://doi.org/10.1371/journal.pone.0014395

Martínez-Porchas, M., and Martínez-Córdova, L.R. (2012). World aquaculture: Environmental impacts and troubleshooting alternatives. *The Scientific World Journal*, 2012, 389623. https://doi.org/10.1100/2012/389623

Mastor, N.N.I., Zuldin, W.H., Faudzi, N.M., Rodrigues, K.F., and Ransangan, J. (2025). Fish hybridization: enhancing genetic potential, ecological implications and ethical perspectives. *International Journal of Agriculture and Biosciences,* 14(3), 374-387. https://doi.org/10.47278/journal.ijab/2024.015

Masuma, S., and Aoki, R. (2024). Maturation in a hybrid grouper, Kue-Tama, a cross between female longtooth grouper, *Epinephelus bruneus*, and male giant grouper, *E. lanceolatus*. *Aquaculture International,* 32, 3481–3498. https://doi.org/10.1007/s10499-023-01333-y

McKenzie, D.J., Geffroy, B., and Farrell, A.P. (2021). Effects of global warming on fishes and fisheries. *Journal of Fish Biology,* 98,1489-1492. https://doi.org/10.1111/jfb.14762

McMahon, T. (2000). Regulation and monitoring of marine aquaculture in Ireland. *Journal of Applied Ichthyology,* 16(4), 156-161. https://doi.org/10.1046/J.1439-0426.2000.00263.X

Meldgaarda, T., Alain J. Crivellib, A. J., Jesensekc, D., Poizat, G., Rubind, J.F., and Berrebi, P. (2007). Hybridization mechanisms between the endangered marble trout (*Salmo marmoratus*) and the brown trout (*Salmo trutta*) as revealed by in-stream experiments. *Biological Conservation*, 136, 602-611. https://doi.org/10.1016/j.biocon.2007.01.004

Micheli, F., Leo, G.D., Shester, G.G., Martone, R.G., Lluch-Cota, S.E., Butner, C., Crowder, L.B., Fujita, R., Gelcich, S., Jain, M., Lester, S.E., McCay, B., Pelc, R., and Saenz-Arroyo, A. (2014). A system-wide approach to supporting improvements in seafood production practices and outcomes. *Frontiers in Ecology and the Environment*, 12(5), 297-305. https://doi.org/10.1890/110257

Miranda, C.D., Tello, A., and Keen, P.L. (2013). Mechanisms of antibiotic resistance in finfish aquaculture. *Frontiers in Microbiology*, 4, 233. https://doi.org/10.3389/fmicb.2013.00233

Mitra, A., Abdel-Gawad, F. K., Bassem, S., Barua, P., Assisi, L., Parisi, C., Temraz, T.A., Vangone, R., Kajbaf, K., Kumar, V., and Guerriero, G. (2023). Climate Change and Reproductive Biocomplexity in Fishes: Innovative Management Approaches towards Sustainability of Fisheries and Aquaculture. *Water,* 15, 725-740. https://doi.org/10.3390/w15040725

Moyson, S., Liew, H.J., Diricx, M., Sinha, A.K., Blust, R., and Boeck, G.D. (2015). The combined effect of hypoxia and nutritional status on metabolic and ionoregulatory responses of common carp (*Cyprinus carpio*). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology,* 179, 133-143. https://doi.org/10.1016/j.cbpa.2014.09.017

Muhlfeld, C.C., Kovach, R.P., Jones, L.A., Al-Chokhachy, R., Boyer, M.C., Leary, R.F., Lowe, W.H., Luikart, G., and Allendorf, F.W. (2014). Invansive hybridization in a threatened species is accelerated by climate change. *Nature Climate Change*, 4, 620-624. https://doi.org/10.1038/nclimate2252

Munday, P.L., Warner, R.R., Monro, K., Pandolfi, J.M., and Marshall, D.J. (2013). Predicting evolutionary responses to climate change in the sea. *Ecology Letters,* 16(12), 1488–1500. https://doi.org/10.1111/ele.12185

Murawski, S.A. (2000). Definitions of overfishing from an ecosystem perspective. *ICES Journal of Marine Science,* 57, 649-658. https://doi.org/10.1006/jmsc.2000.0738

Murray, A.G., and Peeler, E.J. (2005). A framework for understanding the potential for emerging diseases in aquaculture. *Preventive Veterinary Medicine*, 67(2-3), 223-235. https://doi.org/10.1016/j.prevetmed.2004.10.012

Mushtaq, M.W., Qadiri, S.S.N., Khan, I.A., Mattoo, A., Shakeel, U., & Shabir, A. (2025). Breeding Technology for Sustainable Aquaculture and Food Security: Current Advancements and Future Prospects. In *Food Security, Nutrition and Sustainability Through Aquaculture Technologies* (pp. 95-105). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-75830-0_6

Mustafa, S., Senoo, S., and Luin, M. (2013). Response of pure stock of coral reef tiger grouper and hybrid grouper to simulated ocean acidification. *International Journal of Climate Change: Impacts and Responses,* 5(1), 47-54. https://doi.org/10.18848/1835-7156/CGP/v05i01/37196

Naish, K.A., Taylor, J.E., Levin, P.S., Quinn, T.P., Winton, J.R., Huppert, D., and Hilborn, R. (2007). An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. *Advances in Marine Biology*, 53, 61-194. https://doi.org/10.1016/S0065-2881(07)53002-6

Naylor, R., Fang, S., and Fanzo, J. (2023). A global view of aquaculture policy. *Food Policy*, *116*, 102422. https://doi.org/10.1016/j.foodpol.2023.102422

Ng, W., and Hanim, R. (2007). Performance of genetically improved nile tilapia compared with red hybrid tilapia fed diets containing two protein levels. *Aquaculture Research*, 38(9), 965-972. https://doi.org/10.1111/j.1365-2109.2007.01758.x

Nielsen, H.M., Ødegård, J., Olesen, I., Gjerde, B., Ardo, L., Jeney, G., and Jeney, Z. (2010). Genetic analysis of common carp (*Cyprinus carpio*) strain: 1: Genetic parameters and heterosis for growth traits and survival. *Aquaculture*, 304(1-4), 14-21. https://doi.org/10.1016/j.aquaculture.2010.03.016

Olesen, I., Gjedrem, T., Bentsen, H.B., Gjerde, B., and Rye, M. (2003). Breeding programs for sustainable aquaculture. *Journal of Applied Aquaculture*, *13*(3–4), 179–204. https://doi.org/10.1300/J028V13N03_01

Opuszynski, K., Shireman, J.V., Aldridge, F.J., and Rottmann, R. (1985). Intensive culture of grass carp and hybrid grass carp larvae. *Journal of Fish Biology*, 26(5), 563-573. https://doi.org/10.1111/j.1095-8649.1985.tb04297.x

Osborne, J.A. (2011). The potential of the hybrid grass carp as a weed control agent. *Journal of Freshwater Ecology,* 1(4), 353-360. https://doi.org/10.1080/02705060.1982.9664053

Park, A., Nam, Y.K., Douglas, S.E., Johnson, S.C., and Kim, D.S. (2003). Genetic characterization, morphometrics and gonad development of induced interspecific hybrids between yellowtail flounder, *Pleuronectes ferrugineus* (Storer) and winter flounder, *Pleuronectes americanus* (Walbaum). *Aquaculture Research*, 34, 389-396. https://doi.org/10.1046/j.1365-2109.2003.00816.x

Pérez, J. (2003). Aquaculture and the environment: The risks and rewards. *Journal of Applied Aquaculture*, 5(1), 45-56. https://doi.org/10.1300/J108v05n01_07

Pérez-Ramírez, M., Martínez-González, M.A., and Delgado-Andrade, C. (2020). Consumer perceptions and acceptability of genetically improved and hybrid fish. *Journal of Consumer Affairs*, 54(2), 346-362.

Prabu, E., Rajagopalsamy, C., Ahilan, B., Jeevagan, I., and Renuhadevi, M. (2019). Tilapia- an excellent candidate species for world aquaculture: A review. *Annual Research and Review in Biology*, 31(3), 1-14. https://doi.org/10.9734/arrb/2019/v31i330052

Protection of Fishery Resources Act 1951 (No. 313, Chapter II). Japanese Law Translation Database System. Ministry of Justice, Japan.

Pullan, S., and Smith, P.J. (1987). Identification of hybrids between koi (*Cyprinus carpio*) and goldfish (*Carassius auratus*). *New Zealand Journal of Marine and Freshwater Research,* 21, 41-46. https://doi.org/10.1080/00288330.1987.9516198

Rahman, M., Arshad, A., Marimuthu, K., Ara, R., and Amin, S. (2013). Inter-specific hybridization and its potential for aquaculture of fin fishes. *Asian Journal of Animal and Veterinary Advances*, 8(1), 139-153. https://doi.org/10.3923/AJAVA.2013.139.153

Reed, T.E., Prodohl, P., Hynes, R., Cross, T., Ferguson, A., and McGinnity, P. (2015). Quantifying heritable variation in fitness-related traits of wild, farmed and hybrid Atlantic salmon families in a wild river environment. *Heredity,* 115,173-184. https://doi.org/10.1038/hdy.2015.29

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd,K. A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., and Cooke, S.J. (2018). Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Review*, 94(3), 849-873. https://doi.org/10.1111/brv.12480

Reisenbichler, R.R., Utter, F.M., and Krueger, C.C. (2003). Genetic concepts and uncertainties in restoring fish populations and species. *American Fisheries Society*, 149-183.

Roberts, D.G., Gray, C.A., West, R.J., and Ayre, D.J. (2010). Marine genetic swamping: hybrids replace an obligately estuarine fish. *Molecular Ecology*, 19, 508-520. https://doi.org/10.1111/j.1365-294X.2009.04501.x

Robinson, N.A., Gjedrem, T., and Quillet, E. (2017). Improvement of disease resistance by genetic methods. In G. Jeney, (Ed,). *Fish Diseases: Prevention and Control Strategies* (pp. 21-50). Academic Press. https://doi.org/10.1016/B978-0-12-804564-0.00002-8

Rosenfield, J.A., Nolasco, S., Lindauer, S., Sandoval, C., and Kodric-Brown, A. (2004). The role of hybrid vigor in the replacement of pecos pupfish by its hybrids with sheepshead minnow. *Biology Conservation*, 18(6), 1589-1598. https://doi.org/10.1111/j.1523-1739.2004.00356.x

Roy, S., Kumar, V., Behera, B.K., Parhi, J., Mohapatra, S., Chakraborty, T., and Das, B.K. (2022). CRISPR/Cas genome editing-can it become a game changer in future fisheries sector?. *Frontier in Marine Science,* 9, 924475. https://doi.org/10.3389/fmars.2022.924475

Salgotra, R.K., and Chauhan, B.S. (2023). Genetic diversity, conservation, and utilization of plant genetic resources. *Genes*, *14*(1), 174. https://doi.org/10.3390/genes14010174

Sampantamit, T., Ho, L.T., Lachat, C., Sutummawong, N., Sorgeloos, P., and Goethals, P. (2020). Aquaculture production and its environmental sustainability in Thailand: Challenges and potential solutions. *Sustainability*, 12(5), 2010. https://doi.org/10.3390/su12052010

Sanches-Fernandes, G.M., Sá-Correia, I., and Costa, R. (2022). Vibriosis outbreaks in aquaculture: addressing environmental and public health concerns and preventive therapies using gilthead seabream farming as a model system. *Frontiers in Microbiology*, *13*, 904815. https://doi.org/10.3389/fmicb.2022.904815

Sarker, B.S., Ali, A., Rahman, S.S., Alam, M.S., and Islam, M.S. (2024). Monogamous hybridization of Nile tilapia (*Oreochromis niloticus*) with Mozambique tilapia (*O. mossambicus*) results in unprecedented all-female F1 hybrid. *Aquaculture and Fisheries*. https://doi.org/10.1016/j.aaf.2024.04.007

Sato, T., Watanable, K., Arizono, M., Mori, S., Nagoshi, M., and Harada, Y. (2008). Intergeneric hybridization between sympatric kirikuchi char and red-spotted masu salmon in a small Japanese mountain stream. *North American Journal of Fisheries Management*, 28:247-556. https://doi.org/10.1577/M06-270.1

Semeniuk, C., Capelle, P., Dender, M., Devlin, R., Dixon, B., Drown, J., Heath, J., Hepburn, R.I., Higgs, D., Janisse, K., Lehnert, S., Love, O., Mayrand, J. L., Mickle, M., Pitcher, T., Neff, B., Semple, S., Smith, J.L., Toews, S.D., Wellband, K., and Heath, D. (2019). Domestic-wild hybridization to improve aquaculture performance in chinook salmon. *Aquaculture*, 734255. https://doi.org/10.1016/J.AQUACULTURE.2019.734255

Semple, A.L., Heath, G., Filice, C.T., Heath, D.D., and Dixon, B. (2021). The impact of outbreeding on the immune function and disease status of eight hybrid chinook salmon crosses after *Vibrio anguillarum* challenge. *Aquaculture Research*, 53(3), 957-973. https://doi.org/10.1111/are.14887

Servili, A., Lévêque, E., Mouchel, O., Devergne, J., Lebigre, C., Roussel, S., Mazurais, D., and José-Luis Zambonino-Infante, J-L. (2023). Ocean acidification alters the acute stress response of a marine fish. *Science of the Total Environment*, 858, 159804. https://doi.org/10.1016/j.scitotenv.2023.159804

Shapawi, R., Abdullah, F. C., Senoo, S., and Mustafa, S. (2018). Nutrition, growth and resilience of tiger grouper (*Epinephelus fuscoguttatus*) × giant Grouper (*Epinephelus lanceolatus*) hybrid-a review. *Reviews in Aquaculture*, *11*(4), 1285-1296. https://doi.org/10.1111/raq.12292

Siegwarth, G.L., and Summerfelt, R.C. (1993). Performance comparison and growth models for walleyes and walleye× sauger hybrids reared for two years in intensive culture. *The Progressive Fish-Culturist*, 55(4), 229-235. https://doi.org/10.1577/1548-8640(1993)055<0229:PCAGMF>2.3.CO;2

Šimková, A., Civáňová, K., and Vetešník, L. (2022). Heterosis versus breakdown in fish hybrids revealed by one-parental species-associated viral infection. *Aquaculture*, 546, 737406. https://doi.org/10.1016/j.aquaculture.2022.737406

Šimková, A., Vojtek, L., Halačka, K., Hyršl, P., and Vetešník, L. (2015). The effect of hybridization on fish physiology, immunity and blood biochemistry: A case study in hybridizing *Cyprinus carpio* and *Carassius gibelio* (Cyprinidae). *Aquaculture*, 435, 381-389. https://doi.org/10.1016/j.aquaculture.2014.09.029

Snow, A.A., Andow, D.A., Gepts, P., Hallerman, E.M., Power, A., Tiedje, J.M., and Wolfenbarger, L.L. (2005). Genetically engineered organisms and the environment: Current Status and recommendations. *Ecological Applications*, 15(2), 377-404. https://doi.org/10.1890/04-0539

Sonesson, A.K., Hallerman, E., Humphries, F., Hilsdorf, A.W.S., Leskien, D., Rosendal, K., Bartley, D., Hu, X., Gomez, G., and Mair, G.C. (2023).

Sustainable management and improvement of genetic resources for aquaculture. *Journal of the World Aquaculture Society*, *54*(2), 364-396. https://doi.org/10.1111/jwas.12968

Stankus, T. (2010). U.S. farm-raised catfish. *Journal of Aquatic Food Product Technology*, 19(4), 303-316. https://doi.org/10.1080/10496505.2010.492284

Stanley, J.G. (2011). Production of hybrid, androgenetic, and gynogenetic grass carp and carp. *Transactions of the American Fisheries Society*, 105(1), 10-16.

Stickney, H.L., Schmutz, J., Woods, I.G., Holtzer, C.C., Dickson, M.C., Kelly, P. D., Myers, R.M., and Talbot, W.S. (2002). Rapid mapping of zebrafish mutations with SNPs and oligonucleotide microarrays. *Genome Research,* 12, 1929–1934. https://doi.org/10.1101/gr.777302

Su, J., Wang, Z., Zhang, Y., Yan, X., Li, Q., and Yu, R. (2016). Early embryo and larval development of inviable intergeneric hybrids derived from *Crassostrea angulata* and *Saccostrea cucullate. Journal of Ocean University of China,* 15, 515-522. https://doi.org/10.1007/s11802-016-2877-0

Sui, J., Liu, Q., Xiao, Z., Ma, D., Xu, S., He, T., Liu, Y., Xiao, Y., and Li, J. (2013). The viability, melanophore and embryo genesis of first- and second-generation hybrids between *Paralichthys olivaceus* and *P. dentatus*. *Marine Biology Research,* 9(2), 220–226. https://doi.org/10.1080/17451000.2012.729843

Suleiman, R., and Rosentrater, K. (2018). Techno-economic analysis (TEA) of extruded aquafeeds. *Journal of Food Research*, 7(5), 57-66. https://doi.org/10.5539/JFR.V7N5P57

Sun, L., Kumar, G., Engle, C., and van Senten, J. (2022). Trends for U.S. catfish and swai products in retail markets. *Aquaculture Economics & Management*, 26(2), 211-225. https://doi.org/10.1080/13657305.2022.2147250

Sun, X., Qiu, X., and Lin, H. (2021). Disease resistance and immune response in hybrid grouper (*Epinephelus lanceolatus* × *Epinephelus coioides*) infected with *Vibrio* spp. *Aquaculture*, 534, 736196

Sundin, J. (2023). The effects of ocean acidification on fishes – history and future outlook. *Journal of Fish Biology,* 103, 765-772. https://doi.org/10.1111/jfb.15323

Sustainable Development Policy on Fisheries and Aquaculture, 2009 (Law No. 11.959). Constitution of the Federative Republic of Brazil.

Teoh, C., Turchini, G.M., and Ng, W. (2011). Genetically improved farmed Nile tilapia and red hybrid tilapia showed differences in fatty acid metabolism when fed diets with added fish oil or a vegetable oil blend. *Aquaculture*, 312(1-4), 126-136. https://doi.org/10.1016/j.aquaculture.2010.12.027

Tiedje, J.M., Colwell, R.K., Grossman, Y.L., Hodson, R.E., Lenski, R.E., Mack, R.N., and Regal, P.J. (1989). The planned introduction of genetically engineered organisms: Ecological considerations and recommendations. *Ecology,* 70(2), 298-315. https://doi.org/10.2307/1937535

Ton, C., Stamatiou, D., Dzau, V.J., and Liew, C.C. (2002). Construction of a zebrafish cDNA microarray: gene expression profiling of the zebrafish during development. *Biochemical and Biophysical Research Communications,* 296, 1134–1142. https://doi.org/10.1016/S0006-291X(02)02021-0

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H., and Fang, J.G. (2020). Integrated multi-trophic aquaculture (IMTA) in marine offshore systems: Ecological engineering. *Aquaculture*, 522, 735128. https://doi.org/10.1016/j.aquaculture.2020.735128

Tuncer, H., Harrel, R.N., and Houdem E.D. (1990). Comparative energetics of striped bass (*Morone saxatilis*) and hybrid (*M. saxatilis* × *M. chrysops*) juveniles. *Aquaculture,* 86(4), 387-400. https://doi.org/10.1016/0044-8486(90)90269-I

United States (1980). *National Aquaculture Act of 1980 [as amended through Public Law 107-293, Nov 13, 2002). U.S. Government Printing Office, California*

Verdegem, M., Buschmann, A.H., Latt, U.W., Dalsgaard, A.J., and Lovatelli, A. (2023). The contribution of aquaculture systems to global aquaculture production. *Journal of the World Aquaculture Society*, *54*(2), 206-250. https://doi.org/10.1111/jwas.12963

Wang, Z., Pu, D., Zheng, J., Li, P., Lü, H., Wei, X., Li, M., Li, D., and Gao, L. (2023). Research has shown that hypoxia can make fish more vulnerable to diseases. *Ecotoxicology and Environmental Safety,* 267, 115609. https://doi.org/10.1016/j.ecoenv.2023.115609

Yamashita, Y.T., Aritaki, M., Kurita, Y., and Tanaka, M. (2014). Early growth and development of reciprocal hybrids of the starry flounder *Platichthys stellatus* and stone flounder *Kareius bicoloratus*. *Journal of Fish Biology,* 84(5), 1503–1518. https://doi.org/10.1111/jfb.12376

Ye, Y.Y., Zhu, B., Yun, J., Yang, Y., Tian, J., Xu, W., Du, X., Zhao, Y., and Li, Y. (2024). Comparison of antioxidant capacity and immune response between low salinity tolerant hybrid and normal variety of Pacific white shrimp (*Litopenaeus vannamei*). *Aquaculture International,* 32, 1879-1894. https://doi.org/10.1007/s10499-024-01097-x

Yoon, D.E., Lee, H., and Kim, K. (2023). Recent research trends in stem cells using CRISPR/Cas-based genome editing methods. *International Journal of Stem Cells*, 16(3), 345-360. https://doi.org/10.15283/ijsc23030

Yu, D., Xiao, Z., Liu, Q., Xu, S., Ma, D., Li, J., and Webb, K.A. (2010). Ontogeny of gastrointestinal tract in hybrid flounder Jasum, *Paralichthys olivaceus* × *P. dentatus*. *Journal of the World Aquaculture Society,* 41(3), 344–357. https://doi.org/10.1111/j.1749-7345.2010.00376.x

Yue, G.H., and Wang, L. (2017). Current status of genome sequencing and its applications in aquaculture. *Aquaculture*, 468, 363-369. https://doi.org/10.1016/j.aquaculture.2016.11.038

Zabidi, A., Yusoff, F.M., Amin, N., Yaminudin, N.J.M., Puvanasundram, P., and Karim, M.M.A. (2021). Effects of probiotics on growth, survival, water quality and disease resistance of red hybrid tilapia (*Oreochromis* spp.) fingerlings in a biofloc system. *Animals*, *11*(12), 3514. https://doi.org/10.3390/ani11123514

Zhang, C., Jiang, S., Tian, Y., Dong, X., Xiao, J., Lu, Y., Liang, T., Zhou, H., Xu, D., Zhang, H., Luo, M., and Xia, Z. (2023). Smart breeding driven by advances in sequencing technology. *Modern Agriculture*, 1(1), 43-56. https://doi.org/10.1016/j.modac.2023.02.005

Zhang, Y., Wei, H., and Zhao, Z. (2020). Advances in hybridization and genetic improvement of carp species. *Aquaculture*, 523, 735104. https://doi.org/10.1016/j.aquaculture.2020.735104

Zhao, Y., Zhang, C., Zhou, H., Song, L., Wang, J., and Zhao, J. (2020). Transcriptome changes for Nile tilapia (*Oreochromis niloticus*) in response to alkalinity stress. *Comparative Biochemistry and Physiology Part D: Genomics and Proteomics*, 33, 100651. https://doi.org/10.1016/j.cbd.2019.100651

Zhou, L., and Gui, J.F. (2018). Applications of genetic breeding biotechnologies in Chinese aquaculture. *Aquaculture in China: Success Stories and Modern Trends*, 463–496. https://doi.org/10.1002/9781119120759.CH6_1

Zhu, Z., Zhu, Y., and Qin, Y. (2021). Genetic diversity and performance of hybrid fish populations: Insights from recent studies. *Aquaculture International*, 29(1), 15-31. https://doi.org/10.1007/s10499-020-00620-7

Zon, L.I., and Peterson, R.T. (2005). *In vivo* drug discovery in the zebrafish. *Nature Review Drug Discovery,* 4, 35-44. https://doi.org/10.1038/nrd1606