SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 12, No. 1.1, (2026), pp. 3609-3617
Open Access. Online & Print

DOI: 10.5281/zenodo.121.126264

APPLIED GENETICS: ALTERNATIVE MEASURE FOR THE POTENTIATION OF SUSTAINABLE AQUACULTURE

Neil Gallardo Garcia[1*]

Universidad del Magdalena, ngallardogarcia@gmail.com, https://orcid.org/0009-0001-0324-0697

Received: 11/12/2025
Accepted: 20/01/2026

Corresponding Author: Neil Gallardo Garcia (ngallardogarcia@gmail.com)

ABSTRACT

This paper reviews the crucial role of applied genetics in sustainable aquaculture, focusing on several key dimensions: genetic management, disease resistance, nutrition, and resource conservation. The application of genetics facilitates the selection and enhancement of aquatic species, enhancing productivity and fostering greater resistance to diseases. This is a pivotal consideration in environments where pathologies can lead to population decline. The article goes on to explore advanced techniques such as assisted genetic selection and gene editing, which facilitate the identification of desirable traits, improving the health and growth of organisms. These tools optimize production and promote animal welfare, as well as adaptation to changing environmental conditions, thus contributing to the sustainability of the sector. The article also explores the relationship between genetics and nutrition, highlighting how genetic enhancement can influence feed efficiency and the quality of the final product. This is crucial to minimize resource loss and maximize profitability. The article concludes with a discussion of the economic and ecological benefits of implementing sustainable genetic practices. The conclusion of the article asserts that the implementation of applied genetics is an innovative and necessary strategy to ensure the long-term viability of aquaculture, thereby helping to address global challenges such as climate change and overexploitation of natural resources.

KEYWORDS: Aquaculture, Genetic Management, Conservation, Nutrition, Sustainability.

1. INTRODUCTION

Aquaculture, a food industry with a notable degree of growth in recent decades, has undergone substantial expansion since 1990. During the period spanning from 1990 to 2020, the total global aquaculture sector experienced a 609% surge in annual production, exhibiting an average annual growth rate of 6.7% (FAO, 2020). However, the sector is confronted with substantial challenges pertaining to sustainability and production efficiency, which have led to a gradual decline in the average annual growth rate from 9.5% during the period 1990-2000 to 4.6% during the period 2010-2020. The rate of growth further slowed in recent years, reaching 3.3% per year from 2015 to 2020 (FAO, 2020).

Globally, more than 600 species of fish are farmed in aquaculture. This encompasses both freshwater and saltwater fish species, with a total distribution of 494 distinct species, 7 fish hybrids, 94 species groups identified at the genus level, and 57 species groups identified at the family level or higher (FAO, 2000).

Aquaculture has undergone significant expansion to meet the mounting global demand for fish, encompassing a diverse array of species with varied nutritional requirements and farming methodologies (Gonzales, 2002). As the global demand for high-quality protein continues to rise, the need to enhance productivity without compromising natural resources becomes paramount. In this context, the responsible use of genetics emerges as a promising alternative to address these challenges (Berger, 2020).

The employment of genetic techniques in aquaculture has facilitated substantial advancements in the enhancement of farmed species. These techniques encompass a wide range of approaches, from the conventional practice of genetic selection to the more recent development of genome editing. These methodologies have proven to be effective in increasing growth rate, improving disease resistance, and optimizing adaptation to variable environmental conditions (FAO, 2009). For instance, genetic selection has been employed with success in species such as turbot and sea bass, leading to notable enhancements in economic and health-related characteristics (Martínez, 2012; Montero et al., 2023). The advent of genome editing, facilitated by technologies such as CRISPR/Cas9, has engendered novel prospects for the precise modification of specific genes, thereby enhancing resilience against parasites like lice in sea salmon populations. (Vera, 2022). However, despite these advancements, numerous farmed species continue to exhibit substantial genetic similarity to their wild counterparts, indicating significant potential for enhancing production through genetic enhancement.

In summary, the integration of genetic techniques in aquaculture not only improves the efficiency and sustainability of production, but also these efforts are transforming aquaculture into an activity aligned with market demands and environmental challenges. Collaboration between industry, administration, and research centers is essential to continue advancing in this field and to make the most of the potential of genetics applied to aquaculture. This article delves into the various applications of genetics in aquaculture, their associated benefits, and the prospects for this industry.

2. FUNDAMENTALS OF GENETICS

In 1866, Gregorio Mendel published the results of his experiments, which demonstrated that biological inheritance could be explained and predicted by a series of laws. Despite its initial publication, it was not until the late nineteenth century that Mendel's laws were rediscovered, owing to the discovery of chromosomes and their behavior during cell division, as well as the increased use of mathematics in biology. This development marked the genesis of a novel scientific discipline, which, in 1906, came to be known as Genetics.

The Chromosomal Theory of Inheritance, also known as the Mendelian Theory of Genetics, represents a subsequent theoretical breakthrough that is associated with genetic mapping (Casanueva et al., 2008).

The Law of Uniformity stipulates that the mating of two pure lines that differ in a specific trait result in F1 individuals exhibiting the same phenotype, irrespective of the direction of crossbreeding (Smith, 2023).

The Law of Segregation: Also known as the Law of Independent Distribution, it states that, during the formation of gametes, the alleles of a gene separate or segregate independently of each other. This law is fundamental in Mendelian genetics and explains how alleles for a given trait are randomly distributed in the offspring (Hartl et al., 2021).

The Law of Independent Combination, alternatively, stipulates that the alleles of a gene do not interact during the process of gamete formation. This law posits that, during the process of gamete formation, the alleles of distinct genes are distributed independently of one another. This principle underscores that the inheritance of one trait is not contingent upon the inheritance of another, and that alleles from distinct genes amalgamate randomly in the offspring (Griffiths et al., 2020). These laws are applicable in many fields, including aquaculture,

where they can be used to improve the production and quality of aquatic species.

2.1. Genetic Improvement

The integration of genetic tools with biological principles in various disciplines of aquaculture facilitates the augmentation of genetic variation within hydrobiological organisms, irrespective of species, with the objective of ensuring the identification of superior specimens based on genealogical records and data analysis. This approach utilizes reproductive techniques to replicate the genetic material and to select the most suitable specimens within their respective groups.

2.2. Selection and Genetic Improvement Techniques

Selective breeding is a technique that involves the selection and cross-breeding of individuals with specific genetic characteristics to enhance traits such as growth, disease resistance, and feed efficiency. This technique is predicated on the evaluation of the performance and characteristics of the parents and the selection of those with the greatest genetic potential. Charo et al. (2006) evaluated the effectiveness of selective breeding in Oreochromis niloticus, demonstrating significant improvements in several traits of aquaculture importance. In the case of tilapia, the researchers implemented a selective breeding program over several generations, with a focus on selecting individuals with higher growth rates and resistance to diseases. The results demonstrated that, after five generations of selective breeding, the selected fish exhibited growth rates that were 15-20% higher than those of the unselected individuals. The study concluded that selective breeding is highly effective in improving productive traits, contributing to greater profitability and sustainability in aquaculture systems.

Hybridization, defined as the crossbreeding of individuals from different species to combine advantageous traits, such as increased growth, disease resistance, or tolerance to adverse environmental conditions, is a key component of aquaculture. This process has been shown to improve productivity and efficiency in farmed species, such as tilapia and carp. Furthermore, hybrids frequently exhibit heterosis, which is defined as superior performance in comparison to their parental species. However, effective management is imperative to avert potential challenges related to adaptability or the erosion of genetic biodiversity within natural ecosystems. A notable example is the red tilapia, which is the result of hybridization between several species of the genus Oreochromis, such as mossambicus, niloticus, aureus, and hornorum. Its coloration, reminiscent of highly commercial fish such as red snapper, has spurred hybridization programs that have led to the development of new lines, thereby enhancing their suitability for aquaculture (Campo, 2003; Camero et al., 2018).

Genetic enhancement in fish has undergone substantial progress in recent years, propelled by the necessity to augment the efficiency of aquaculture. This progression is associated with the evolution of conventional methods towards high-precision instruments based on modern biotechnology (Ponzoni et al., 2005). Initially, fish selection was based on phenotypic criteria, that is, on selecting individuals with physical characteristics, for example, larger, healthier individuals or with better reproductive characteristics. While these rudimentary methods yielded satisfactory outcomes in certain aspects of population enhancement, they were contingent on natural genetic variability and did not consider the impact of specific genes (Bentsen et al., 2002). The advent of quantitative genetics subsequently enabled a more scientific approach. Through recurrent selection, farmers initiated a systematic cross-breeding process, targeting the optimal individuals within each generation, thereby progressively enhancing sought-after traits, such as growth or disease resistance. However, this approach was implemented only after the fact and was constrained by the inherent limits of visible genetic variability (Martínez et al., 2009; Gjedrem et al., 2012).

3. BIOTECHNOLOGY AND MOLECULAR GENETICS

The transformative impact on genetic improvement was precipitated by the advent of biotechnology and genomics (Liu, 2007).

Beginning in the 1990s, marker-assisted selection (MAS) introduced a paradigm shift in the field of aquaculture, leveraging genetic information to identify and select the optimal broodstock from a given population. These techniques have contributed to a reduction in the environmental impact of aquaculture, enhancing the sustainability and productivity of farmed species, including salmon, tilapia, and carp. This approach also facilitated the identification of specific genes or DNA segments associated with traits of interest, thereby enabling the selection of broodstock with greater precision. Subsequent advancements in DNA sequencing technologies have enabled researchers to map the complete genome of aquatic species of commercial interest, thereby facilitating the adoption of genomic

selection, a method that utilizes information from thousands of genetic markers to more accurately predict the genetic outcomes of each cross (Pérez et al., 2010; Yáñez, et al., 2010; Gjedrem, 2012; Yáñez, et al., 2015).

Genomic sequencing and analysis techniques

Sanger sequencing was used to study DNA fragments and obtain basic genetic information from species such as tilapia and salmon. However, this technique has recently been used by Gaffney et al. (2021) who compare whole genome sequencing and genetic variability in cod. Likewise, it has been used to determine genetic variability in species of commercial interest (Li et al., 2017; Carreiro et al., 2023).

The advent of next-generation sequencing (NGS) platforms, such as the Illumina and Ion Torrent, has enabled the sequencing of entire genomes and transcriptomes, leading to the identification of crucial genetic variations (SNPs and CNVs). These variations have enhanced the efficacy of marker-assisted selection (MAS) and genomic selection (GS) programs (Franco et al., 2021; Kumar et al., 2017). These techniques enabled more precise selection of individuals with desirable traits, such as rapid growth and disease resistance (Lu et al., 2020). Subsequently, third-generation sequencing, exemplified by technologies such as PacBio and Oxford Nanopore, ushered in a paradigm shift within the field by generating longer DNA reads, thereby facilitating the assembly of complex genomes and the study of structural variations. These techniques have also been useful for metagenomics and epigenetic studies, expanding the ability to analyze microbial communities and gene regulation in response to environmental factors. These innovations have not only facilitated a more profound genetic understanding of aquatic species but also enabled the optimization of their production and sustainability in global aquaculture (Kumar et al., 2022). Applications of CRISPR and gene editing in aquaculture.

The advent of gene-editing tools such as CRISPR-Cas9 has facilitated the direct modification of genes in fish's DNA, thereby expediting the breeding process. This has led to notable advances, such as fish with greater disease resistance and better feed conversion, without relying exclusively on selection based on natural crosses (Luo et al., 2022; Yang et al., 2022; Li et al., 2014).

Ohama et al. (2020) used CRISPR-Cas9-based gene editing and determined a 17% increase in skeletal muscle in juveniles of Pagrus major. Concurrent findings have been documented in Salmo Salar by Edvardsen et al. (2014) and Andersson et al. (2024).

In this regard, the selection of fish for genetic enhancement has progressed from rudimentary phenotypic assessments to advanced techniques underpinned by genomics and gene editing. These advancements have led to substantial improvements in aquaculture yields, enhancing the efficiency, speed, and sustainability of the process while concurrently mitigating the risks associated with inbreeding and safeguarding the genetic biodiversity of the cultivated species.

4.CONSERVATION OF GENETIC RESOURCES

4.1. The Importance of Genetic DiversityiIn Fish Populations

Genetic diversity is imperative for the adaptation, survival, and ecological stability of fish populations. Greater genetic variability enables species to better cope with environmental changes, such as variations in temperature, salinity, or food availability (Mancera et al., 2013; Hermoza et al., 2021). Furthermore, genetic diversity has been demonstrated to reduce the likelihood of diseases severely affecting a population, as certain genetic variants can confer resistance (Tibihika et al., 2020). Conversely, the loss of biodiversity, attributable to overexploitation, pollution, or the introduction of exotic species, can diminish the resilience of aquatic ecosystems and elevate the risk of extinction for certain species (Lieke et al., 2020; Pinsky et al., 2014). Consequently, the conservation of genetic diversity emerges as a pivotal element in the sustainable management of fisheries resources.

4.2. Strategies for the Conservation of Aquaculture Species

Biogenetic strategies for the conservation of aquaculture species prioritize the preservation and augmentation of genetic diversity, ensuring the resilience of populations to environmental threats, diseases, and climate change (Camarena 2024).

Cryopreservation of genetic material: The freezing and storage of gametes (sperm and eggs), embryos, or even tissues allow the genetic diversity of endangered aquaculture species to be preserved. This technique is valuable for future genetic restoration programs, ensuring the availability of genetic material even in the event of a dramatic decline in natural populations (Bustamante et al., 2019).

Genetic Resource Banks (GRBs), in conjunction

with Assisted Reproductive Technologies (ART), have the potential to mitigate biodiversity loss and promote sustainable development. GRBs encompass the collection, processing, storage, and application of germplasm (semen, eggs, embryos, tissues) and other biomaterials (blood products, DNA samples) (Medina et al., 2020). The primary function of GRBs is to preserve viable genetic material over extended periods and at low temperatures. They serve as pivotal instruments in the conservation and repopulation of threatened or endangered species, as well as in the enhancement of commercial species with limited genetic diversity. The most prevalent method employed in these cryobanks is cryopreservation in liquid nitrogen (Martínez et al., 2017; Guaje et al., 2023). Recent studies have demonstrated the efficacy of this technique. For instance, Calizaya et al. (2023) observed that there were no significant differences in the percentage of fertilization of fresh semen and cryopreserved semen in the species Colossoma macropomum.

Biotechnology and gene editing. The advent of sophisticated tools such as CRISPR has rendered feasible the modification of the DNA of aquaculture species, thereby introducing disease resistance genes or enhancing their capacity to adapt. Despite the potential of this technique, it is imperative to exercise caution in its application to mitigate the possibility of unintended ecological consequences and to adhere to established ethical and environmental regulations (Dunham, 2023).

Genetic monitoring of populations: The genetic diversity of natural and cultivated populations can be assessed using DNA sequencing and other technologies. This information is crucial for identifying populations at risk of genetic diversity loss and for developing interventions to conserve them (Pandey et al., 2021).

Murillo et al. (2023) identified high levels of genetic diversity in the snapper Lutjanus guttatus. They also found that there is no evidence of differentiation into genetic subpopulations, which in fisheries management is considered a single panmictic population. These results were acquired through the use of microsatellites for population monitoring. Concurrently, Díaz et al. (2023) identified the genetic connectivity of L. guttatus between Mexico and Panama.

The genetic characterization and monitoring of stocks are used in both fisheries and aquaculture. In Cuba, Pérez et al. (2017) employed four loci microsatellites to characterize six stocks of Litopenaeus vannamei utilized for aquaculture.

To put it succinctly, the implementation of genetic monitoring for fish populations can facilitate the optimization of management strategies, contribute to the preservation of their natural habitats, and encourage the adoption of fishing practices that are more sustainable in the long term.

4.3. Genetics and Disease Resistance

In the context of aquaculture, the development of disease resistance has emerged as a critical.

Table I. Some References of Genetic Improvement Applications for Resistance to Pathogens.

Application	Pathogen	Species	Authors
Marker-assisted selection (MAS)	Infectious Pancreatic Necrosis Virus (IPNV)	*Salmo Salar*	Godoy et al., (2022)
Traditional genetic selection	*Streptococcus iniae*	*Oreochromis niloticus*	Sánchez et al. (2022)
Identifying SNP Markers	*Piscirickettsia salmonis*	*Oncorhynchus mykiss*	Rodriguez (2017)
Genome editing	White spot syndrome virus (WSSV)	*Penaeus vannamei*	Castro (2024)
Genetic mapping	Herpesvirus Koi (Khawar)	*Cyprinus carpio*	Jia et al., (2020)
Heritability	White spot syndrome virus (WSSV)	*Penaeus vannamei*	Cala et al., (2021)

In the context of aquaculture, the development of disease resistance has emerged as a critical concern, given the significant impact that various bacterial, viral, and parasitic diseases can have on production outcomes. The development of resistant fish varieties is imperative to ensure the sustainability and profitability of the aquaculture industry.

Genetic methodologies are employed to study disease resistance in fish. These methodologies include techniques such as marker-assisted genetic selection (MAS), which uses genetic markers to identify individuals with desirable characteristics, such as disease resistance (Herrera, 2022). Furthermore, genome-wide association studies (GWAS) are employed to identify genetic variants associated with resistance, thereby providing insights into the implicated genes (Costas et al., 2024). Next-generation sequencing (NGS) techniques facilitate comprehensive analysis of entire genomes, thereby simplifying the identification of pertinent mutations (Cabrera et al., 2023).

Gene editing methodologies, such as CRISPR/Cas9, are employed to modify specific genes that can confer resistance to pathogens, thereby creating new opportunities for enhancing the health and welfare of fish populations and crustaceans in aquaculture (Marín, 2021). These methodologies were evaluated in hydrobiological species (Table 1). The findings indicate the potential

for successful genetic enhancement of these characteristics, presenting a viable strategy for managing these pathologies. By concentrating on genetic selection and modification, it is feasible to cultivate more disease-resistant fish populations, which would enhance the overall health of crops and potentially diminish reliance on chemical treatments and antibiotics. This approach is predicated on the promotion of more sustainable practices in aquaculture and the potential for increased productivity and profitability in the long term. Furthermore, by addressing the underlying causes of disease susceptibility, genetic enhancement can contribute to the resilience of populations to future environmental and pathological challenges.

4.4. Nutrition and Genetics

The interaction between genetics and nutrition in fish is intricate and bears significant ramifications for the domains of aquaculture and conservation. A comprehensive understanding and optimization of this relationship can result in more efficient and sustainable practices, thereby enhancing fish health and welfare (Pérez, 2022).

The gut microbiota, being a dynamic component of the organism, adapts to environmental conditions and interacts with the genetic profile of the organism, influencing various aspects such as growth, health, and disease resistance (Peredo et al., 2024). These intricate interactions underscore the necessity of incorporating microbiota considerations into genetic enhancement programs, as a balanced microbiota has been shown to enhance gut health and, consequently, productive performance (Oña et al., 2020).

Conversely, the efficacy of functional foods, which are formulated to promote health, can vary depending on the genetics of the fish. For instance, certain strains may benefit more from specific prebiotics or probiotics, suggesting that a personalized dietary approach, informed by genetics, can optimize the benefits of the gut microbiota (do Nascimento et al., 2019; Pérez, 2022).

In summary, the relationship between microbiota, genetics, and nutrition is a promising field that can significantly contribute to improving efficiency and sustainability in aquaculture. Integrating this knowledge into breeding programs can yield more robust and resilient fish populations.

5. CONCLUSIONS

The present study demonstrates that applied genetics is a pivotal instrument in the promotion of sustainable aquaculture. It facilitates the cultivation of fish families that exhibit enhanced disease resistance, thereby reducing reliance on chemical treatments and promoting an ecological approach. Through genetic selection, feed conversion is optimized, thereby decreasing the amount of feed required to achieve a given yield and consequently reducing the environmental impact. Genetic enhancement has also been demonstrated to boost growth rate and total production, thereby addressing the expanding global demand for high-quality protein while safeguarding the economic sustainability of aquaculture enterprises. Integrating genetics with effective management and nutrition practices is paramount to fully realizing the benefits of genetic enhancement and ensure the well-being of fish populations. Finally, continuous research in applied genetics is essential to innovate and face future challenges, ensuring sustainable development in the aquaculture sector.

REFERENCES

Andersson, E., Schulz, R. W., Almeida, F., Kleppe, L., Skaftnesmo, K. O., Kjærner-Semb, E., ... & Wargelius, A. (2024). Loss of Fisher prevents testicular maturation in Atlantic salmon (Salmo salar). Endocrinology, 165(4), bqae013.

Bentsen, H. B., y Olesen, I. (2002). Design of breeding programs for aquaculture species: Possibilities and constraints. Aquaculture Research, 33(1), 79-89.

Berger, C. (2020). La acuicultura y sus oportunidades para lograr el desarrollo sostenible en el Perú. South Sustainability, 1(1), e003 DOI: 10.21142/SS-0101-2020-003

Bustamante-González, J. D., Rodríguez-Gutiérrez, M., Cortés-García, A., Arenas-Ríos, E., Figueroa-Lucero, G., & Ávalos-Rodríguez, A. (2019). Fisiología y criopreservación del espermatozoide en teleósteos. AquaTIC, (53), 1-17.

Cabrera, J. M., Bachetta, C., Elías, D. E., & Rueda, E. C. (2023). Identificación de genes a partir de transcriptomas en peces de extensivo uso comercial. Aplicaciones para acuicultura. Ciencia, Docencia y Tecnología Suplemento, 13(14).

Cala-Moreno, N., Campos-Montes, G., Caballero-Zamora, A., Berruecos-Villalobos, J., & Castillo-Juárez, H. (2021). Interacción genotipo por ambiente en camarón blanco asociada a Síndrome de Mancha Blanca. Abanico veterinario, 11.

Calizaya, E. Y. L., & Calizaya, E. N. L. (2023). Efecto de dos tiempos de criopreservación y dos crioprotectores, sobre la viabilidad del semen de (Colossoma macropomum) "gamitana". REBIOL, 42(2), 126-140.

Camarena, J. E. L. (2024). Futuras innovaciones en el sector acuícola. Acta Pesquera, 10(19), 17-25.

Camero-Escobar, G., y Calderón-Calderón, H. (2018). Vigilancia tecnológica e inteligencia competitiva para la producción de tilapia roja (Oreochromis mossambicus) en el departamento del Huila, Colombia. Rev.investig.desarro.innov, 9(1), 19-31. doi: Carreiro, A.

Campo-Castillo, L. F. (2003). Tilapia roja (Oreochromis spp.), una evolución de 22 años: de la incertidumbre al éxito. Cali, Colombia.

Casanueva, M., Méndez, D. (2008) Teoría y experimento en Genética Mendeliana: una exposición en imágenes THEORIA. Revista de Teoría, Historia y Fundamentos de la Ciencia, vol. 23, Universidad del País Vasco/Euskal Herriko Unibertsitatea Donostia-San Sebastián, España.10.19053/20278306.v9. n1.2018.8504.

Castro Obeso, J. G. (2024). Desarrollo de una metodología de edición genómica basada en la entrega in ovo de Cas9 en Penaeus vannamei (Master's thesis, Centro de Investigaciones Biológicas del Noroeste, SC).

Charo-Karisa H, Komen J, Rezk MA, Ponzoni RW, Van Arendonk J, Bovenhuis H. Heritability estimates and response to selection for growth of Nile tilapia (Oreochromis niloticus) in low-input earthen ponds. Aquacult 2006; 261:479-486.

Costas Imbernón, D., Otero, S., García-Fernández, P., Touriñán, P., Tur, R., Chavarrías, D., ... & Saura, M. (2024). Esclareciendo la base genética de las malformaciones pigmentarias en rodaballo.

Díaz-Viloria, N., Max-Aguilar, A., Rivera-Lucero, M. I., Espino-Barr, E., Reguera-Rouzaud, N., Casaucao-Aguilar, A., & Perez-Enriquez, R. (2023). Genetic connectivity in the spotted rose snapper Lutjanus guttatus (Lutjaniformes: Lutjanidae) between Mexico and Panama throughout the Tropical Eastern Pacific. Neotropical Ichthyology, 21(2), e220113.

do Nascimento Trennepohl, F. T., Moura, K., Yoshida, S., Grave, G., dos Santos Oliveira, M., & Severo, J. (2019). Prebióticos e probióticos e os estudos de nutrigenética e nutrigenômica. Boletim Técnico-Científico, 5(2).

Dunham, R. (2023). Aquaculture and fisheries biotechnology: genetic approaches. Cabi.

Edvardsen, R. B., Leininger, S., Kleppe, L., Skaftnesmo, K. O., & Wargelius, A. (2014). Targeted mutagenesis in Atlantic salmon (Salmo salar) using the CRISPR/Cas9 system induces complete knockout individuals in the F0 generation. PloS one, 9(9), e108622.

FAO. (2000). El estado mundial de la pesca y la acuicultura 2000. FAO Información División. Roma: 142 pp.

FAO. (2009). Desarrollo de la acuicultura. 3. Gestión de recursos genéticos. FAO Orientaciones Técnicas para la Pesca Responsable. No. 5, Supl. 3. Roma, FAO. 148p.

FAO. (2020). El estado mundial de la pesca y la acuicultura 2020. La sostenibilidad en acción. Roma. https://doi.org/10.4060/ca9229es.

Franco, C. M., Ambrosio, R. L., Cepeda, A., & Anastasio, A. (2021). Fish intended for human consumption: From DNA barcoding to a next-generation sequencing (NGS)-based approach. Current Opinion in Food Science, 42, 86-92.

Gjedrem, T. (2012). Genetic improvement for the development of efficient global aquaculture: A personal opinion review. Aquaculture, 344-349, 12-22.

Gjedrem, T., Robinson, N., y Rye, M. (2012). The importance of selective breeding in aquaculture to meet future demands for animal protein: A review. Aquaculture, 350-353, 117-129.

Godoy, M., Kibenge, M. J., Montes de Oca, M., Pontigo, J. P., Coca, Y., Caro, D., ... & Kibenge, F. S. (2022). Isolation of a New Infectious Pancreatic Necrosis Virus (IPNV) Variant from Genetically Resistant Farmed Atlantic Salmon (Salmo salar) during 2021–2022. Pathogens, 11(11), 1368.

Gonzales-Laxe, F., La acuicultura y el desarrollo económico (2002). Departamento de Economía Aplicada. Facultad de Ciencias Económicas. Universidad de A Coruña. A Zapateira, s/n. E-15071 A Coruña, España.

Griffiths, J., Miller, J., Suzuki, T. (2020). An Introduction to Genetic Analysis (12th ed.). W. H. Freeman.

Guaje, D., & Medina-Robles, V. M. (2023). Antioxidantes en la crioconservación de semen de peces: una revisión con énfasis en especies de agua dulce de Sur América. Orinoquia, 27(2).

Hartl, D., Jones, E. (2021). Genetics: Analysis of Genes and Genomes (9th ed.). Jones & Bartlett Learning.

Hermoza, G. F., Orihuela, C., Fernández, K., Arévalo, P., Ccahuana, W., Campos, A., & Iannacone, J. (2021). Paiche (Arapaima gigas) (Cuvier, 1829) (Osteoglossiformes: Arapaimidae): una revisión sistemática de

la diversidad genética para la conservación del pez gigante del Amazonas. Revista Campus, 26(31).
Herrera Canales, E. S. (2022). Herramientas en ingeniería genética usadas para mejorar el crecimiento y supervivencia en el cultivo de peces.
Jia, Z., Chen, L., Ge, Y., Li, S., Peng, W., Li, C., ... & Xu, P. (2020). Genetic mapping of Koi herpesvirus resistance (KHVR) in Mirror carp (Cyprinus carpio) revealed genes and molecular mechanisms of disease resistance. Aquaculture, 519, 734850.
Kumar, G., & Kocour, M. (2017). Applications of next-generation sequencing in fisheries research: A review. Fisheries Research, 186, 11-22.
Kumar, P., Gundappa, M. K., & Ram, (2022) M. R. K. MinION-A Third Generation Portable Nanopore Sequencer: Potential Applications in Fisheries and Aquaculture.
Li, M., Yang, H., Zhao, J., Fang, L., Shi, H., Li, M., & Wang, D. (2014). Efficient and heritable gene targeting in tilapia by CRISPR/Cas9. Genetics, 197(2), 591-599.
Li, Y. H., & Wang, H. P. (2017). Advances of genotyping-by-sequencing in fisheries and aquaculture. Reviews in Fish Biology and Fisheries, 27(3), 535-559.
Lieke, T., Meinelt, T., Hoseinifar, S. H., Pan, B., Straus, D. L., & Steinberg, C. E. (2020). Sustainable aquaculture requires environmental-friendly treatment strategies for fish diseases. Reviews in Aquaculture, 12(2), 943-965.
Liu, Z. J. (2007). Aquaculture Genome Technologies. Wiley-Blackwell.
Lu, G., & Luo, M. (2020). Genomes of major fishes in world fisheries and aquaculture: Status, application and perspective. Aquaculture and Fisheries, 5(4), 163-173.
Luo, M., Wang, J., Dong, Z., Wang, C., & Lu, G. (2022). CRISPR-Cas9 sgRNA design and outcome assessment: Bioinformatics tools and aquaculture applications. Aquaculture and Fisheries, 7(2), 121-130.
Mancera-Rodríguez, N. J., Marquez, E. J., & Hurtado-Alarcón, J. C. (2013). Uso de citogenética y técnicas moleculares en estudios de diversidad genética en peces colombianos. Biología Molecular aplicada a la producción animal y la conservación de especies silvestres. Medellin: Ed. Universidad Nacional de Colombia (Medellín), 237-312.
Marín Carrasco, D. M. (2021). Microinyección como metodología de entrega de material de edición a través de CRISPR/Cas9 en Penaeus vannamei (Master's thesis, Centro de Investigaciones Biológicas del Noroeste, SC).
Martínez P. (2005). Aplicaciones de la genética para la mejora de la acuicultura. Departamento de Genética. Facultad de Veterinaria. Universidad de Santiago de Compostela. Campus de Lugo. E-27002 Lugo, España.
Martínez, P. (2012) Genómica y Acuicultura: aplicaciones para la mejora de la producción de rodaballo AquaTIC, núm. 37, pp. 16-19 Universidad de Zaragoza Zaragoza, España
Martínez, V., & Neira, R. (2009). Advances in genetic improvement of Chilean salmon farming: The SalmoGen breeding program. Aquaculture Research, 41(8), 170-178.
Martínez-Páramo S, Horváth Á, Labbé C, Zhang T, Robles V, Herráez P, Suquet M, Adams S, Viveiros A, Tiersch TR & Cabrita E. Cryobanking of aquatic species. Aquaculture, 2017; 472: 156-177
Medina-Robles, V. M., Duarte-Trujillo, A. S., & Cruz-Casallas, P. E. (2020). Crioconservación seminal en peces de agua dulce: aspectos biotecnológicos, celulares y bioquímicos. Orinoquia, 24(2), 51-78.
Medina-Robles, V. M., Guaje-Ramírez, D. N., Marin-Cossio, L. C., Sandoval-Vargas, L. Y., & Cruz-Casallas, P. E. (2019). Crioconservación seminal de (Colossoma macropomum) como estrategia de producción y conservación en la Orinoquia Colombiana. Orinoquia, 23(1), 15-24.
Montero, D., Carvalho, M., Terova, G., Fontanillas, R., Serradell, A., Ginés, R., Tuset, V., Acosta, F., Rimoldi, S., Bajek, A., Haffray, P., Allal, F. & Torrecillas, S. (2023). Nutritional innovations in superior European sea bass (Dicentrarchus labrax) genotypes: Implications on fish performance and feed utilization. Aquaculture, Volume 572, 739486, ISSN 0044-8486.
Murillo-Rios, A., Ramirez-Flores, S., Barquero-Chanto, J. E., Peña-Navarro, N., & Pérez-Enríquez, R. (2023). Genetic variability of the fish Lutjanus guttatus (Perciformes: Lutjanidae) using microsatellites in Costa Rica. Revista de Biología Tropical, 71(1).
Ohama, M., Washio, Y., Kishimoto, K., Kinoshita, M., & Kato, K. (2020). Growth performance of myostatin knockout red sea bream (Pagrus major) juveniles produced by genome editing with CRISPR/Cas9. Aquaculture, 529, 735672.
Oña, L. E. A. (2020). Alimentación y nutrición en peces de agua dulce. Revista Estudiantil Agro-Vet, 4(2), 604-

608.
Pandey, P. K., & Parhi, J. (Eds.). (2021). Advances in fisheries biotechnology (p. 521). Springer.
Peredo, A. A. A., Alba, J. C. R., & Pantoja, M. D. (2024). Nutrición molecular: La interacción entre la alimentación y nuestros genes. + Ciencia, (36), 27-30.
Pérez-Beloborodova, A., Artiles-Valor, A., Pérez-Jar, L., Hernández-Martínez, D., Guerra-Aznay, M., & Espinosa-López, G. (2012). Genetic Characterization of Six Stocks of Litopenaeus vannamei used in Cuba for Aquaculture by means of Microsatellite Loci. International Journal of Zoology, 2012(1), 352165.
Perez-Enriquez, R., &Taniguchi, N. (2010). Application of molecular markers and genomics in aquaculture genetic improvement. Current Genomics, 11(4), 246-257.
Pérez-Sánchez, J. (2022). Importancia de la microbiota en acuicultura. Interacción nutrición, ambiente y genética.
Pinsky, M. L., & Palumbi, S. R. (2014). Meta-analysis reveals lower genetic diversity in overfished populations. Molecular ecology, 23(1), 29-39.
Ponzoni, R. W., Hamzah, A., Tan, S., & Kamaruzzaman, N. (2005). Genetic improvement of Nile tilapia (Oreochromis niloticus) with special reference to the work conducted by the WorldFish Center with the GIFT strain. Aquaculture, 246(1-4), 27-30.
Ramírez-Fernández, P. E., Veloz-Atencio, E. E., & Miranda-Quiroga, R. (2018). Estudio estratégico para el desarrollo sostenible de la acuicultura de agua dulce en Camagüey. Revista de Producción Animal, 30(1), 58-65.
Rodríguez Huanca, F. H. (2017). Identificación de marcadores SNP (polimorfismo de nucleótido único) asociados a la resistencia frente al virus de la necrosis pancreática infecciosa (IPN) en truchas arcoíris (Oncorhynchus mykiss).
Rodriguez-Pulido, José A.; Cruz-Casallas, P., & Gongora-Orjuela, A. (2016). Hibridización de silúridos: una alternativa para la piscicultura con alto riesgo para la conservación de las especies nativas. Orinoquia, vol.20, n.1, pp.62-68. ISSN 0121-3709.
Sánchez Roncando, C. O., & Fonseca de Freitas, R. T. (2022). Supervivencia observada en tres familias de tilapia del Nilo (Oreochromis niloticus) infectadas con Streptococcus agalactiae. Revista de la Facultad de Medicina Veterinaria y de Zootecnia, 69(3), 236-244.
Scotto-Espinoza, C. & Arriola-Prieto, C. (2017). Hibridación y determinación del patrón de herencia de los colores y otros rasgos por cruzamiento recíproco entre cuatro variedades consanguíneas domésticas con la variedad silvestre del pez ornamental guppy, (Poecilia reticulata) peters (pisces, osteichthye). Cátedra Villarreal. 5. 63-85. 10.24039/cv201751188.
Smith, J. (2023) "Mendel's Law of Uniformity Revisited: Insights from Modern Genetics." Journal of Genetics and Molecular Biology, vol. 25, no. 2, pp. 112-125.
Tibihika, P. D., Curto, M., Alemayehu, E., Waidbacher, H., Masembe, C., Akoll, P., & Meimberg, H. (2020). Molecular genetic diversity and differentiation of Nile tilapia (Oreochromis niloticus, L. 1758) in East African natural and stocked populations. BMC Evolutionary Biology, 20, 1-20.
Vera-Tamargo, F. (2022). Implementación del sistema CRISPR/Cas9 para la edición génica en fagocitos de salmón del Atlántico. Disponible en https://repositorio.uchile.cl/handle/2250/193442
Yáñez, J. M., & Martínez, V., (2010). Factores genéticos que inciden en la resistencia a enfermedades infecciosas en salmónidos y su aplicación en programas de mejoramiento. Arch Med Vet 42, 1-13.
Yáñez, J. M., Newman, S., y Houston, R. D. (2015). Genomics in aquaculture: Advances and opportunities in the application of genomic selection for breeding programs. Aquaculture, 450, 117-125.
Yang, Z., Yu, Y., Tay, Y. X., & Yue, G. H. (2022). Genome editing and its applications in genetic improvement in aquaculture. Reviews in Aquaculture, 14(1), 178-191.