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Exploring the Morphological Foundations of Fish Culture: A Review

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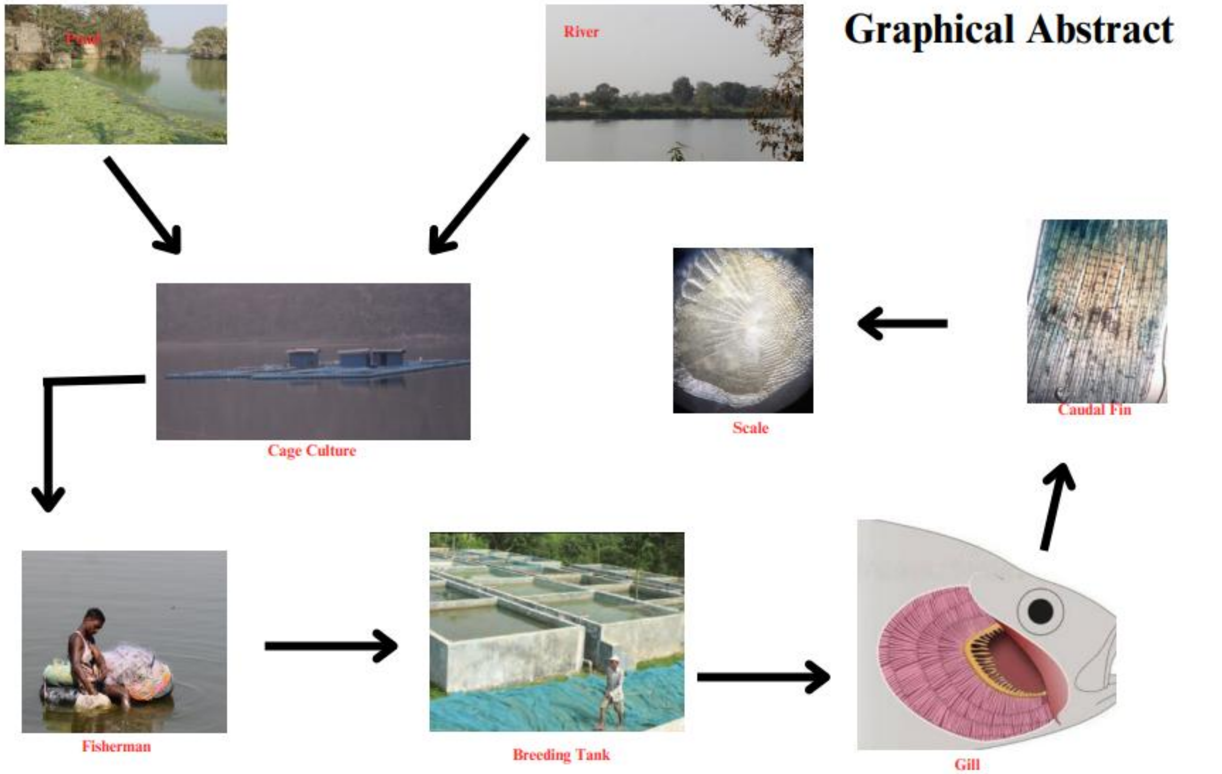
Abstract

Fish culture, or aquaculture, has become a critical component of global food production, and understanding the morphological foundations of fish species is essential for optimizing breeding, growth, and sustainability in this industry. This review explores the morphological characteristics of key fish species cultivated in aquaculture, focusing on how anatomical traits influence performance in controlled environments. The paper examines aspects such as body shape, fin structure, gill development, and internal organ configuration, highlighting their roles in swimming efficiency, respiration, nutrient absorption, and overall health. Morphological traits also impact disease resistance and adaptability to different aquaculture systems, from freshwater to marine environments. The review further discusses how selective breeding practices can enhance desired morphological features, thereby improving production efficiency and reducing costs. Additionally, the influence of environmental factors such as water quality, temperature, and diet on fish morphology is addressed, underscoring the importance of optimal conditions for growth. By synthesizing current research, this paper provides a comprehensive understanding of the connection between fish morphology and aquaculture practices, with implications for the development of more sustainable, high-yield aquaculture systems. The review also suggests areas for future research, particularly in the genetic and environmental determinants of fish morphology and its application in improving aquaculture practices.

Keywords: Aquaculture; Environmental; Fish culture; Growth; Morphology; Selective breeding.

1. Introduction

The rapid growth of global fish farming an essential component of modern aquaculture has made it one of the most important sectors in the global food production landscape [1]. As the demand for sustainable and protein-rich food sources increases, so too does the need for innovative approaches to fish culture that ensure both high yields and environmental sustainability [2]. One of the fundamental, yet often underexplored, aspects of aquaculture that directly influences the success and efficiency of fish farming systems is the morphology of fish species [3]. From body shape to skeletal development, fin structure to organ function, the physical form of fish is more than just a biological feature; it is a critical determinant of their performance, adaptability, and overall health in a controlled farming environment [4]. Exploring the Morphological Foundations of Fish Culture: A Review aims to provide an in-depth understanding of how fish



morphology shapes the practice of fish farming [5]. This comprehensive review delves into the intricate relationship between fish physical characteristics and the efficiency of aquaculture operations [6].

It offers a synthesis of current research, case studies, and expert analyses that highlight the importance of various morphological traits, including body size, fin configuration, skeletal structure, and physiological adaptation to environmental factors such as water quality, stocking density, and stress conditions [7]. At its core, this article seeks to bridge the gap between theoretical morphological science and practical aquaculture application [8]. By examining the direct and indirect ways in which fish morphology influences growth rates, reproductive success, disease resistance, feed efficiency, and welfare, this volume serves as a foundational resource for researchers, aquaculture practitioners, and policymakers alike [9]. Moreover, it explores how understanding these morphological underpinnings can lead to the development of more efficient farming techniques, improved breeding programs, and ultimately, the sustainability of fish culture in an increasingly resource-limited world [10]. As the aquaculture industry continues to expand, the need for precision in breeding, management practices, and species selection has never been more critical [11].

Through a detailed exploration of the morphological characteristics of key fish species, it offers a roadmap for improving the productivity and sustainability of fish culture practices worldwide [12]. Fish culture, or aquaculture, has become an integral part of global food production, providing a sustainable source of protein and contributing significantly to economic development [14]. As the demand for aquatic products rises, understanding the biological and ecological underpinnings of fish farming becomes crucial for optimizing production practices and ensuring the health and well-being of cultured species [15]. Among the key biological factors influencing aquaculture, fish morphology plays a fundamental role in shaping growth patterns, reproductive success, disease resistance, and overall performance in cultured environments [16]. Morphological characteristics, such as body shape, fin structure, and skeletal development, are not only essential for the physical fitness of fish but also for their adaptability to various environmental conditions and farming systems [17]. Moreover, these traits can impact feed efficiency, water quality management, and the ability to withstand stressors such as overcrowding or pathogen exposure [18]. This review aims to explore the morphological foundations of fish culture, examining how various physical attributes influence the success of fish farming operations [19].

By synthesizing current research and highlighting key morphological considerations, this review provides valuable insights for aquaculture practitioners, researchers, and policymakers seeking to enhance the sustainability and productivity of fish culture worldwide [20].

2. Review of Literature

By examining the morphological basis of force generation in the chelae (claws) of both molluscivorous and non-molluscivorous crabs, it is possible to understand better the difference between general crab claw design and the morphology associated with durophagy. This comparative study investigates the morphology underlying claw force production and intraspecific claw dimorphism in six brachyuran crabs: Callinectes sapidus (Portunidae), Libinia emarginata (Majidae), Ocypode quadrata (Ocypodidae), Menippe mercenaria (Xanthidae), Panopeus herbstii (Xanthidae), and P. obesus (Xanthidae). The crushers of the three molluscivorous xanthids consistently proved to be morphologically 'strong,' having largest mechanical advantages (MAs), mean angles of pinnation (MAPs), and physiological cross-sectional areas (PCSAs) (Schenk, S. C., and Wainwright, P. C., 2001) [21].

Despite being currently considered the solid ground of communication studies, or better because of it, culture needs radical reformulation. The antiquated perspective on culture defined it as an idealized abstraction, as a means of distinguishing human beings and the variety of their social groups, as well as an edge severing humanity from the natural world. In that sense, culture is conceived as a set of immanent rules of social integration, whose purpose is to separate what is ours in opposition to what is other. The distinctions are neat: social groups are different because they have different cultures, and culture draws a line disengaging human beings from both animal and natural life (Neiva, E., 2002) [22].

Climbing perch locally known as koi (Anabas testudineus) is a popular food fish in our country. Thai climbing perch was introduced in Bangladesh from Thailand. To explore the variation in growth performance and morphological features of local and Thai climbing perch a study was undertaken. The highest gain in length, weight and SGR were found in Thai koi 12.23±0.38 em, 55.83±0.53 g and 7.92±0.11 %/day respectively.

Fourteen morphometric characters were studied where eleven (TL, SL, HL, HBD, LBD, DFL, PECFL, PELFL, AFL, UJL and LJL) showed significant difference in Thai koi from the local ones. Of the meristic characters no. of dorsal fin rays (hard), anal fin rays (hard), caudal fin rays and scale along lateral line (upper and lower) as recorded from the Thai koi were significantly higher (Alam, M. A., et. al., 2004) [23].

However, the discovery of morphological computation,1 [C. Paul, Investigation of Morphology and Control in Biped Locomotion, Ph.D. Thesis, Department of Computer Science, University of Zurich, Switzerland, 2004], the phenomenon that computation can be obtained through interactions of physical form, elucidates a possible mechanism underlying this relationship. The fact that simple physical interactions give rise to computation indicates the theoretical possibility for the dynamics of the morphology to play a computational role in the system, and thereby to subsume part of the role of control. Thus, it may serve to analyse the relationship between morphology and control, and guide the design of robots with reduced control requirements.

The goal of the paper is to explore this possibility. The paper introduces the concept of morphological computation in the context of robot morphology, discusses its potential role in the morphology and control trade-off, and then uses it as a basis to develop a heuristic for the design of robots with reduced control requirements. The heuristic is then tested through experiments to validate its accuracy (Paul, C., 2006) [24].

Recent years have witnessed a re-evaluation of the cognitive capabilities of fishes, including with respect to social learning. Indeed, some of the best experimental evidence for animal traditions can be found in fishes. Laboratory experimental studies reveal that many fishes acquire dietary, food site and mating preferences, predator recognition and avoidance behaviour, and learn pathways, through copying other fishes.

Concentrating on foraging behaviour, we will present the findings of laboratory experiments that reveal social learning, behavioural innovation, the diffusion of novel behaviour through populations and traditional use of food sites.

Further studies reveal surprisingly complex social learning strategies deployed by sticklebacks. We will go on to place these observations of fish in a phylogenetic context, describing in which respects the learning and traditionality of fish are similar to, and differ from, that observed in other animals. We end by drawing on theoretical insights to suggest processes that may have played important roles in the evolution of the human cultural capability (Laland, K. N., Atton, N., & Webster, M. M., 2011) [25].

A unisexual species is generally associated with polyploidy, and reproduced by a unisexual reproduction mode, such as gynogenesis, hybridogenesis or parthenogenesis. Compared with other unisexual and polyploid species, gibel carp (Carassius auratus gibelio) has a higher ploidy level of hexaploid. It has undergone several successive rounds of genome polyploidy, and experienced an additional, more recent genome duplication event. More significantly, the dual reproduction modes, including gynogenesis and sexual reproduction, have been demonstrated to coexist in the polyploid gibel carp. This article reviews the genetic basis concerning polyploidy origin, clonal diversity and dual reproduction modes, and outlines the progress in new variety breeding and gene identification involved in the reproduction and early development. As a novel evolutionary developmental (Evo-Devo) biology model, this work highlights future perspectives about the functional divergence of duplicated genes and the sexual origin of vertebrate animals (Gui, J., & Zhou, L., 2010) [26].

In fishes the shape of the body and the swimming mode generally are correlated. Slender-bodied fishes such as eels, lampreys, and many sharks tend to swim in the anguilliform mode, in which much of the body undulates at high amplitude. Fishes with broad tails and a narrow caudal peduncle, in contrast, tend to swim in the carangiform mode, in which the tail undulates at high amplitude. Such fishes also tend to have different wake structures. Carangiform swimmers generally produce two staggered vortices per tail beat and a strong downstream jet, while anguilliform swimmers produce a more complex wake, containing at least two pairs of vortices per tail beat and relatively little downstream flow (Tytell, E. D., et.al., 2010) [27].

The taxonomic uncertainty surrounding cryptic species complexes has traditionally been resolved using lengthy experimental approaches, while, since the advent of PCR based techniques the number of cryptic species described in a variety of taxa is increasing steadily. Here we formally describe a new rotifer species of the Brachionus plicatilis complex: Brachionus manjavacas n.sp., disentangling what was known as a morphological stasis. Detailed morphological analyses demonstrated significant differences in body shape and size between B. manjavacas and B. plicatilis s.s., analysed by geometric morphometrics; unfortunately these statistical differences are not taxonomically reliable because of wide overlaps. Size and asymmetry of masticatory apparatus, named trophi, observed by SEM, gave similar results, with taxonomic ambiguity (Fontaneto, D., Giordani, I., Melone, G., & Serra, M.,2007) [28].

The potential use of sequencing batch reactors (SBRs) as an alternative bio-flocs technology (BFT) approach in aquaculture was explored. One SBR was dosed with glycerol and one with acetate for the decrease of the nitrogen concentration in simulated aquaculture water by microbial assimilation. At an optimal C/N ratio between 10 and 15, the nitrogen removal efficiency reached up to 98% (= 110 mg N L^{-1} reactor day^{-1}) for both SBRs. The estimated biomass productivity reached 0.62–0.94 g C L^{-1} reactor day^{-1} for the glycerol SBR and 0.54–0.82 g C L^{-1} reactor day^{-1} for the acetate SBR. The floc protein content, indicating biomass quality, reached up to 57% if grown on glycerol. With acetate, it attained a value of 61%. The highest average poly-β-hydroxybutyrate (PHB) content was 16% on a dry weight basis for the acetate biomass (De Schryver, P., & Verstraete, W., 2009) [29].

Flavobacterium psychrophilum is a serious pathogen in trout aquaculture, responsible for the diseases rainbow trout fry syndrome (RTFS) and cold water disease (CWD). Bacteriophage control of F. psychrophilum may constitute a realistic approach in the treatment of these diseases; however, a detailed understanding of the phage-host interactions is needed to evaluate the potential of F. psychrophilum bacteriophages for that purpose. Twenty-two F. psychrophilum phages from Danish rainbow trout farms were isolated and characterized (Stenholm, A. R., Dalsgaard, I., & Middelboe, M., 2008) [30].

Tuna and related scombrid fishes are high-performance swimmers that often operate at high frequencies, especially during behaviors such as escaping from predators or catching prey. This contrasts with most fish-like robotic systems that typically operate at low frequencies (< 2 hertz). To explore the high-frequency fish swimming performance space, we designed and tested a new platform based on yellowfin tuna (Thunnus albacares) and Atlantic mackerel (Scomber scombrus). Body kinematics, speed, and power were measured at increasing tail beat frequencies to quantify swimming performance and to study flow fields generated by the tail. Experimental analyses of freely swimming tuna and mackerel allow comparison with the tuna-like robotic system. The Tunabot (255 millimeters long) can achieve a maximum tail beat frequency of 15 hertz, which corresponds to a swimming speed of 4.0 body lengths per second (Zhu, J., et. al., 2019) [31].

The fish early-life stage (FELS) test (Organisation for Economic Co-operation and Development [OECD] test guideline 210) is the primary test used internationally to estimate chronic fish toxicity in support of ecological risk assessments and chemical management programs. As part of an ongoing effort to develop efficient and cost-effective alternatives to the FELS test, there is a need to identify and describe potential adverse outcome pathways (AOPs) relevant to FELS toxicity. Using swim bladder inflation as an example, a weight-of-evidence–based approach was used to support linkage of key molecular initiating events to adverse phenotypic outcomes and reduced young-of-year survival. Based on an iterative approach, the feasibility of using key events as the foundation for expanding a network of plausible linkages and AOP knowledge was explored and, in the process, important knowledge gaps were identified (Villeneuve, D., et. al., 2014) [32].

In the present study, Lactobacillus plantarum P8 was used to ferment soybean meal (SBM), resulting in a significant reduction in the indigestible oligosaccharides (sucrose, raffinose, and stachyose) and anti-nutritional factors (tannin, trypsin inhibitors, glycinin, and β-conglycinin) in SBM. Nine isonitrogenic and isoenergetic experimental diets were formulated in which SBM or L. plantarum P8 fermented SBM (LPFSBM) replaced fish meal (FM) protein with 0 (control); 15% by SBM (Diet 1), 30% by SBM (Diet 2), 45% by SBM (Diet 3), 60% by SBM (Diet 4), 15% by LPFSBM (Diet 5), 30% by LPFSBM (Diet 6), 45% by LPFSBM (Diet 7), and 60% by LPFSBM (Diet 8).

Triplicate groups of 30 fish were fed to apparent satiation twice daily for 66 d in an indoor recycling seawater system. No significant differences were found in survival rate among the different groups. However, 45% SBM, 60% SBM, and 60% LPFSBM (Diets 3, 4, and 8) diets significantly reduced growth performance and feed utilization. The LPFSBM diets did not affect moisture, crude protein, crude lipid, or crude ash contents of whole-body measurements (Wang, L., Zhou, H., He, R., Xu, W., Mai, K., & He, G., 2016) [33].

The measurement of species diversity represents a powerful tool for assessing the impacts of human activities on marine ecosystems. Traditionally, the impact of fish farming on the coastal environment is evaluated by monitoring the dynamics of macrobenthic infaunal populations. However, taxonomic sorting and morphology-based identification of the macrobenthos demand highly trained specialists and are extremely time-consuming and costly, making it unsuitable for large-scale biomonitoring efforts involving numerous samples. Here, we propose to alleviate this laborious task by developing protist metabarcoding tools based on next-generation sequencing (NGS) of environmental DNA and RNA extracted from sediment samples. In this study, we analysed the response of benthic foraminiferal communities to the variation of environmental gradients associated with salmon farms in Scotland. We investigated the foraminiferal diversity based on ribosomal minibarcode sequences generated by the Illumina NGS technology (Pawlowski, J., et. al., 2014) [34].

Although most studies on integration and modularity have focused on variation among individuals within populations or species, this is not the only level of variation for which integration and modularity exist. Multiple levels of biological variation originate from distinct sources: genetic variation, phenotypic plasticity resulting from environmental heterogeneity, fluctuating asymmetry from random developmental variation and, at the interpopulation or interspecific levels, evolutionary change. The processes that produce variation at all these levels can impart integration or modularity on the covariance structure among morphological traits (Klingenberg, C. P., 2014) [35].

To determine the differences in morphological characteristics and muscle nutritional quality between largemouth bass (Micropterus salmoides) cultured in an aquaculture system using land-based container with recycling water (C-RAS) and those cultured in a traditional pond system (TP), largemouth bass with no significant difference in body weight were selected. Results showed that the largemouth bass cultured in C-RAS had a significantly longer body and significantly lower condition factor and viscerosomatic index than those cultured in the TP ($P < 0.01$). In terms of muscle characteristics, the water loss and muscle fibre diameter were significantly lower in the C-RAS group than those in the TP group ($P < 0.05$), whereas the firmness, chewiness, springiness, and shear force in the C-RAS group were significantly higher than those in the TP group ($P < 0.01$). The crude protein content was significantly higher in the muscles of largemouth bass cultured in C-RAS than in those cultured in the TP ($P < 0.05$) (Jia, S. P., et. al., 2022) [36].

Fish coloration, evolved from selection and adaptation, is a prominent feature of remarkable aquaculture merits. Fish possess more pigment cell types than any other vertebrates and are an excellent model for the study of mechanisms underlying skin coloration and pigmentation at levels from molecular genetics to system biology. How to effectively improve skin colour in ornamental and aquaculture fish has long been a focus on selective breeding programmes. In this review article, we introduce different types of chromatophore and early development of pigmentation, describe cellular mechanisms related to morphological and physiological changes of body colour and demonstrate applications of single-sex control and molecular marker–assisted breeding in body colour selection (Luo, M., et. al., 2021) [37].

Farmed fish are a promising source of high-quality and sustainable protein. However, the production of farmed fish products that meet food safety standards is one of the major public health challenges worldwide. Therefore, food safety management in fish farms has recently garnered increasing attention. However, the detection of health parameters in fish is currently lacking. Haematology, an approach that is widely used in humans, provides a reliable assessment of health status in a non-lethal and low-cost way. Nevertheless, comprehensive, systemic and standard haematological parameters have not yet been established in farmed fish. Here, we provide a summary of the recent advancements in haematology health indicators in fish. Generally, haematological parameters are based on physiological and biochemical indices in blood (Chen, H., and Luo, D., 2023) [38].

Among the background of developments in automation and intelligence, machine learning technology has been extensively applied in aquaculture in recent years, providing a new opportunity for the realization of digital fishery farming. In the present paper, the machine learning algorithms and techniques adopted in intelligent fish aquaculture in the past five years are expounded, and the application of machine learning in aquaculture is explored in detail, including the information evaluation of fish biomass, the identification and classification of fish, behavioral analysis and prediction of water quality parameters. Further, the application of machine learning algorithms in aquaculture is outlined, and the results are analyzed. Finally, several current problems in aquaculture are highlighted, and the development trend is considered (Zhao, S., et. al., 2021) [39].

We review how seaweed genetic resources are currently used in aquaculture, in relation to the diversification and rapidly increasing use of marine resources. Using a revealing case-study, we summarise the potential for positive societal change, underpinned by the cultivation of eucheumatoid carrageenophytes (species of the red algal genera Eucheuma and Kappaphycus), an activity which has been successfully initiated in many tropical countries to support their economic development. We also review the challenges currently faced by this industry and identify potential threats to the seaweed cultivation sector. Accordingly, we suggest new directions to support the continued development of an economically resilient and environmentally sustainable industry based on the utilisation of genetic resources (Brakel, J., et. al., 2021) [40].

3. Conclusion

The critical role of fish morphology in shaping the success of modern aquaculture practices. As global demand for sustainable, protein-rich food continues to rise, understanding the relationship between fish physical characteristics and aquaculture efficiency becomes increasingly vital. This book highlights how traits such as body shape, fin structure, and skeletal development impact key aspects of fish farming, including growth, disease resistance, and overall performance in diverse farming systems. By bridging theoretical science with practical application, the review provides valuable insights into how morphological factors can optimize breeding, improve feed efficiency, and enhance environmental adaptability.

As the aquaculture industry expands, integrating these morphological foundations will be essential for developing sustainable farming practices, improving productivity, and ensuring the long-term success of fish culture globally. This comprehensive review serves as an essential resource for advancing research, innovation, and management in the field of aquaculture.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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