Review

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Surviving in Changing Waters: A Synthesis of Contemporary Research on Fish Physiology in Combination with Climate Change Parameters

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Review

Surviving in Changing Waters: A Synthesis of Contemporary Research on Fish Physiology in Combination with Climate Change Parameters

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Abstract: Fish physiology is a key field of study in fisheries science, providing a solid foundation for understanding aquatic ecosystems and driving innovation in the aquaculture sector. As aquaculture continues to be a key source of food worldwide, study in this subject has increasingly focused on the implications of climate change, which poses considerable threats to fish and other aquatic species. This review outlines current studies on fish physiological responses to several stressors related with climate change, such as changes in temperature, salinity, disease occurrence, and oxygen levels. The combination of these abiotic and biotic variables is vital, as climate change accelerates pathogen fate and dispersion and alters nutrient dynamics, influencing fish growth and survival. This study also reviews mesocosm experiments and modelling research to illustrate the significance of these interactions in developing sustainable fisheries management and enhancing aquaculture methods. Furthermore, the study identifies current research trends and recommends areas for future research to address the ongoing problems posed by climate change to aquatic resources.

Keywords: fisheries; aquaculture; climate change

1. Introduction

In the field of fisheries science, fish physiology is an essential cornerstone to understanding aquatic ecosystems and, more specifically, driving innovation in the aquaculture sector (Shahjahan et al., 2022). This dynamic research field explores the subtleties of fish adaptation and response to environmental changes, offering vital insights that influence sustainable fisheries management and propel the expansion and productivity of the aquaculture industry. A lot of research has been done on issues related to the development of aquaculture and the sustainability of aquatic resources (Gatta, 2017), since fish farming has historically been a significant source of food for humans. The continuous threat posed by climate change to biotic resources has grown over the past few decades to the point that fish and aquatic life in general are at risk (Change, 2023).

Research on fish physiology is currently examining the combined effects of various stressors resulting from climate change. This is reasonable because there are several ways that climate change affects aquatic ecosystems, including changes in temperature, salinity, diseases, and oxygen levels (Little et al., 2020). Mesocosm experiments and models have been utilised for investigating the biotic and abiotic elements in fish growth in order to address these changes (Hébert et al., 2022).

The interaction of biotic and abiotic elements, particularly the rise in temperature and the impact of infections on fish physiology, are major influencing factors in research methodology (Lindmark et al., 2022). The basis for this approach is the fact that pathogen concentrations increase with temperature due to the effects of climate change (Jahne et al., 2017). Therefore, pathogen infections in farmed or wild fish may have an impact on the physiological growth of fish or possibly cause fish mortality. In addition to the significance of temperature on fish physiology and pathogen growth, the combined effects of environmental factors have also been investigated (Raihan et al., 2023). An approach that is valid as climate change impacts every aspect of the biological chain, resulting in

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highly diversified biota on a large scale. In aquatic ecosystems, salinity, oxygen concentration, and the fate and dispersion of nutrients are the main variables that are assessed. The interactions with climate change are the new framework in which those important factors are currently being tested, despite the fact that their effects on fish physiology and aquaculture have been broadly and extensively researched to date (Little et al., 2020).

The **objectives** of this article are to describe the research that has been done on fish physiology in relation to the ecological factors of climate change, to highlight current research trends in this field, and to offer suggestions for further study.

2. Methodology

This review of the current trends in fish impacts from climate change used a methodology based on comparable techniques applied in contemporary research using metadata analysis and data mining tools (Baykoucheva, 2015; Booth et al., 2016; Fink, 2019; Carugo & Aisenhaber, 2022). In order to meet the requirements of this review, the methodology utilised in these studies was summarised and divided into the eight successive phases outlined. A brief mention is provided: 1. Definition of Scope and Objectives: A clear definition of the scope of the review was made, specifying the research objective, and identifying the key trends to explore within the literature. 2. Literature Search: A thorough search of the literature was carried out utilising databases, academic journals, articles, and other pertinent sources. Certain words and phrases pertaining to the scope of the research were used. Additionally, inclusion and exclusion criteria were used to choose papers, with the majority of those published after 2020 being taken into account. 3. Selection Criteria: Clear criteria for including or excluding papers based on relevance, quality, and methodology were considered, and papers addressing climate change for commercial fish species were prioritised. 4. Data Extraction: To gather pertinent information from chosen papers, a structured data extraction form was created. 5. Quality Assessment: The selected papers' quality and rigour were assessed using appropriate criteria, taking into account factors such as study design, sample representativeness, statistical methods, and potential biases. 6. Synthesis of Results: A summary of each paper's key conclusions was provided, and any recurring themes, patterns, or trends in the chosen literature were assessed. Results have been compared and contrasted to show any consistency or inconsistency. 7. Analysis and Interpretation: The combined data were analysed to derive significant conclusions. The last stage involved interpreting the results in relation to the research question or goal. This was followed by a discussion of any gaps or limitations found in the literature that were noted in the critical review sections. 8. Identify Current Trends: The review was completed by highlighting and discussing emerging and current trends found in the literature and by looking for patterns of change over time or parameters where research is rapidly evolving.

3. Review of Contemporary Research

3.1. Review of the Climate Change Factors in Fish Physiology and Behaviour

The current trend in the study of climate change in fish is to test specific ecological factors, which vary. Visser et al. (2023) consider river discharge and water temperature extremes; Brunner et al. (2023) focus on land cover change; Souza et al. (2023) examine temperature and precipitation effects on fish composition; and Adamek et al. (2023) investigate the interaction between temperature and a viral pathogen (TiLV) in salmonids.

The study conducted by Visser et al. (2023) centres on the application of Life Cycle Assessment (LCA) to evaluate the effects of climate change on the diversity of freshwater fish. Changes in average river discharge as well as extremes in water temperature are taken into account in the methodology. In comparison to earlier techniques, the newly derived characterization factors for greenhouse gas emissions show a 172% higher impact on freshwater fish diversity. Brunner et al. (2023) address the trend of declining freshwater biodiversity brought on by human impacts, especially changes in land cover and climate. In order to show how future land cover projections for South America can be downscaled, a workflow for predicting the future habitat suitability patterns of Colombian fish fauna is presented. Methodological difficulties are acknowledged, particularly when tackling future land cover change and climate change at the same time. The effects of extreme weather events and climate change on fish assemblages in the Rio Minho estuary are examined by Ilarri et al. (2023). According to the study, there has been a noticeable change in fish populations over time, with invasive species predominating and native species declining. While invasive species thrive in high temperatures and extreme weather events, native species are adversely affected by high temperatures and low precipitation.

These studies have two important things in common, which is why they are presented in detail. The first focuses on how freshwater ecosystems are affected by climate change and how it affects fish assemblages, behaviour, and diversity. The second is summed up by extreme weather events that are a result of climate change, which is increasingly being identified as a common factor influencing fish populations. These occurrences cause changes in fish assemblages that affect both invasive and native species. This is significant because invasive species typically predominate, but emigration can also result in cross-pollination. However, the significance of improving methodologies in ecological research is evident in all studies. Whether dealing with Life Cycle Assessment (LCA) or modelling future habitat suitability, methodologies are critical for accurate assessments. Some differences in approaches can be seen in Focus and Scope: Visser et al. (2023) focus on the impact of greenhouse gas emissions on fish diversity, whereas Brunner et al. (2023) investigate the effects of land cover change on freshwater organisms. Ilarri et al. (2023) investigate the effects of climate change and extreme events on fish assemblages in a particular estuary. In conclusion, while there are common themes related to climate change and methodological considerations, the specific ecological factors, geographic scope, and topic focus contribute to a more nuanced understanding of the diverse challenges that freshwater fish face in these ecosystems.

Predragovic et al. (2023) provide an extensive review of the scientific literature on the climate-driven biological and social-ecological effects on marine fish species in European waters, which are under threat from both climate change and fishing pressures. The findings highlight a significant knowledge gap, with nearly two-thirds of species underrepresented in the literature. The majority of the covered species have only a few relevant studies, creating challenges for evidence-based decision-making in governance and management. The lack of research is especially concerning for species listed as critically endangered or endangered by the IUCN, indicating a potential disconnect between scientific attention and conservation urgency. This study's strength lies in its ability to integrate findings into existing initiatives such as those of ICES, IMP, CFP, and EMFF. The study provides valuable insights for organisations seeking to manage marine fish species sustainably by recognising the implications of knowledge gaps. The call for prioritised research areas, adaptive harvest strategies, and marine protected area design is a positive recommendation that is consistent with the overall goals of marine ecosystem conservation. In conclusion, while the study effectively highlights the knowledge gap and its implications, further investigation into the root causes and proactive measures to encourage research would enhance the overall contribution of climate change research in fish physiology.

Additional research looks at the disparity in species representation in the body of knowledge regarding the impacts of climate change on marine fish species in European waters. Three species—Atlantic salmon, European pilchard, and Atlantic Bluefin tuna—are identified as receiving attention in the analysis, with an emphasis on the former two (Predragovic et al., 2023). Their significance to Europe's economy is the reason for this bias. Studies on Atlantic salmon are concentrated in Norway, those on European pilchard in the Mediterranean and Iberian Peninsula, and those on Atlantic bluefin tuna in the Mediterranean, indicating regional biases. The analysis of research trends reveals gaps in geographic coverage, particularly in the Northeast Atlantic, Baltic Sea, and the least represented region, the Baltic Sea, which is one of the world's fastest-warming seas (Huusko and Hyvarinen, 2012; Jokinen et al., 2016; Myrvold et al., 2019; Arevalo et al., 2021; Karcher et al., 2021; Havice et al., 2022). These studies shed light on the species representation imbalance in climate change studies involving European marine fish. The identification of dominant species and regional biases helps to provide a more nuanced understanding of the research landscape. The recognition of the studied species' economic importance is consistent with the prioritisation of commercially significant species in scientific research.

Studies have been conducted to investigate how climate change affects freshwater fish in particular (Visser et al., 2023; Bice et al., 2023; Dorado-Guerra et al., 2023). Visser et al. (2023) address the limitations of previous LCA methodologies, emphasising the importance of including water temperature changes and climate extremes in addition to river discharge. New characterization factors for greenhouse gas emissions reveal previously unknown impacts on freshwater fish diversity. The inclusion of water temperature and climate extremes improves our understanding of the true environmental cost of human activities. The call for greater taxonomic coverage and complementary models represents a forward-thinking approach to more comprehensive LCA methods.

Bice et al. (2023) investigated how tidal barriers, which are built all over the world for various purposes, have a negative impact on fish through reduced connectivity, loss of tidal flux, habitat conversion, and altered freshwater discharge. The study looked at how the effects will worsen as a result of freshwater shortages brought on by an expanding human population, altered freshwater flow patterns, and sea level rise encouraged by climate change. Case studies from various regions demonstrate the complexities of managing tidal barriers and the importance of promoting connectivity and natural ecosystem function. The study effectively describes the various effects of tidal barriers on fish and ecosystems. The inclusion of case studies enhances our understanding of regional variations. The suggested factors for future research and management, such as fish passage and restoring tidal flow, provide practical insights into reducing the negative effects of tidal barriers in a variety of ecosystems.

The vulnerability of surface water quality to elevated nutrient concentrations, exacerbated by climate change, is examined in the study by Dorado-Guerra et al. (2023). It predicts future declines in nitrate, ammonium, phosphorus, and BOD5 status using scenarios related to climate change. To maintain the current status of the water body, the research suggests additional actions, such as a 25% reduction in diffuse nitrate pollution and a 50% reduction in point loads of phosphorus, ammonium, and BOD5. Important new information about the possible effects of climate change on surface water quality is also provided by this study. Practical guidelines are provided for maintaining water quality through the incorporation of pollution reduction recommendations and climate scenarios. More thorough discussions of the study's wider environmental ramifications and the viability of putting the recommended reduction measures into practice, however, would be beneficial.

The above reviewed studies effectively emphasize the need for broader geographic coverage, particularly in understudied regions like the Northeast Atlantic and Baltic Sea. The call for increased scientific efforts in these areas is justified, considering the observable effects of climate change on species in the Baltic Sea, which is among the fastest-warming seas globally. They also underscore the importance of expanding research beyond well-studied regions and species. However, the studies acknowledge that some species with extensive monitoring efforts in the Baltic Sea were not included due to their absence from the European IUCN Red List. While this limitation is acknowledged, the new studies and research could further discuss potential implications and strategies for addressing such challenges in representation. In conclusion, the studies establish a current trend that effectively highlights species and regional biases in climate change studies, with a commendable call for increased research in understudied areas. Addressing limitations and proposing strategies for more inclusive representation would enhance the new research impact. Nevertheless, the findings provide valuable insights for directing future research efforts toward understanding climate-driven effects on marine fish species in European waters.

The commercial fish used in aquaculture from marine and brackish waters have also been the subject of intense research, with seabream and seabass serving as the main research subjects (Haberle et al., 2024; Allen et al., 2023; Seale et al., 2022; Huang et al., 2021; O'Connor et al., 2021). Haberle et

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al. (2024) discuss how gilthead seabream aquaculture is impacted by climate change in the Mediterranean. While there is a positive mid-term outlook with faster growth, there are negative long-term effects, particularly in currently productive farming regions. Climate change increases the time to market size, resulting in up to 36% faster growth. Feed conversion ratio at market size doesn't change much over the course of the two-year culturing period; this is mostly because faster growth occurs in warmer sea water. The long-term effects are more detrimental, particularly in areas of farming that are currently productive. The study's conclusions indicated a favourable mid-term outlook but long-term negative trends, especially in the most productive farming regions.

According to a study by Allen et al., climate change has an impact on oyster reefs and related species in the Chesapeake Bay (2023). In most tested scenarios, oyster biomass increases while that of striped bass and blue crab biomass generally decreases. In most cases, the biomasses of blue crab and striped bass decline. In most scenarios, oyster biomass increases. The implications that are discussed include the relationship between the advantages of restoring oyster reefs and climate change, as well as potential modifications to species biomasses.

Another study conducted by Seale et al. (2022) showed euryhaline fishes have physiological adaptations to tidally changing salinities. Fish are able to adapt to ongoing variations in salinity, and prolactin signaling is being modulated locally rather than centrally. The study's findings highlight the following: tilapia maintain branchial ionocyte populations similarly to SW-acclimated fish; there is a shift from systemic to local modulation of Prl signaling; and fish can maintain osmoregulatory parameters within narrow ranges by compensating for constant and noticeable changes in external salinity.

Huang et al. (2021) claim that fisheries and fish diversity are threatened by global climate change. Freshwater fish have received comparatively less research attention than marine fish, with most studies concentrating on temperate and subtropical regions and demonstrating the detrimental effects of climate change on fish growth both locally and globally. Climate change has an adverse effect on fish growth on a local and global scale. Closing the knowledge gaps about how fish growth is affected by climate change will require more extensive research involving a variety of species and geographical regions.

O' Connor et al. (2021) showed that present and predicted near-future water temperature impacts the growth and foraging in estuarine fishes, especially in the schooling fish types. Five common herding estuary fish were tested: the eastern trumpeter Pelates sexlineatus (Quoy & Gaimard 1824), the eastern fortescue Centropogon australis (White 1790), the yellowfin bream Acanthopagrus australis (Owen, 1853), the fan-belly leather jacket Monacanthus chinensis (Isbeck 1765), and the bridled leatherjacket Acanthaluteres spilomelanurus (Quoy & Gaimard, 1824). Higher water temperatures were found to have an impact on the foraging characteristics of different species, which could alter the local fish groupings. The primary findings point to temperature-dependent growth responses unique to estuary species as well as foraging traits (boldness, escape response, and bite rate) that are impacted by warmer water. The implications point to changes in species dominance and trophic interactions as well as changes in local fish assemblages brought on by rising water temperatures in temperate estuaries.

3.1.2. Mesocosm Fish Experiments for Combination of Aquatic Factors and Climate Change

Predicting the ecological origins and effects of climate change requires a range of methods, such as models, surveys, and experiments. Mesocosms are becoming more and more common in experiments because they serve as a vital link between smaller, more closely regulated microcosm studies (Stewart et al., 2013).

Steward et al. (2013) comprehensively explored the use of mesocosm experiments as a tool for ecological climate change research, discussing topics ranging from experimental guiding to future objectives. Mesocosm trials will remain a crucial component of the ecological puzzle for the foreseeable future, even though we must constantly be aware of their evident limitations (Benton et al., 2007; Cadotte et al., 2005; Fraser and Keddy, 1997). They will surely become more and more

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important tools in the toolkit of the climate-change ecologist, especially when combined with complementary methods like modelling and field surveys. Progress in this approach will enhance our existing limited understanding, since many of the ecological ramifications of climate change are yet uncertain. Large-scale, coordinated experimental facilities are difficult to establish and maintain; comparable investments have been made in other sciences, although they are frequently thought to yield more immediate financial benefits, such as the creation of new technologies (such as the Internet, which is a spin-off). The benefits of climate change research are not as immediate in terms of society, despite the fact that the costs and duration of inactivity will be enormous on a global level. Scientists may only be able to predict broad generalisations about major processes rather than specific details about how individual species behave at local scales due to the complexity of the earth system and how human societies respond to change, but even this is a significant improvement over our current state of affairs (Stewart et al., 2013).

The study conducted by Cole et al. (2021) on rocky shore diversity using mesocosms testing warming and ocean acidification indicated that elevated pCO2 influences the growth of native bivalve mollusk Trichomya hirsuta (Lamarck, 1819) but not the introduced mediterranean mussel Mytilus galloprovincialis (Lamarck, 1819). Warming and pCO2 also impact infaunal communities associated with both mussel species. The shift from one mussel species to another is suggested to significantly influence infaunal communities, emphasizing the ecological consequences of climate-driven changes. Cun et al. (2022) examined reed biomass dynamics under different nutrient levels and revealed a delayed start of the fast-growth phase and varied morphological traits with increasing nutrient enrichment. The findings underscore the crucial role of ambient nutrient supply in temporal variation in plant biomass and morphological traits, shedding light on the complex relationships between nutrient levels and plant growth stages.

Strandberg et al. (2022) investigated the combined effects of climate change and eutrophication on phytoplankton. The study highlighted a significant impact of nutrient treatment on phytoplankton EPA and DHA concentrations. The variation is attributed to changes in phytoplankton community structure rather than direct nutrient or temperature effects, suggesting that eutrophication may pose a greater threat to EPA and DHA production than warming in shallow temperate lakes. The study by Carmo et al. (2023) on commercial Amazon tambaqui fish Colossoma macropomum (G. Cuvier, 1818) explored the effects of climate change on gene expression levels of appetite-regulating peptides in the brain. Temperature and acidity of the water are two environmental effects of climate change that can alter fish metabolism and appetite, thereby influencing fish populations in aquaculture facilities as well as in the wild. Fish exposed to extreme climate scenarios (800 ppm CO_2 and 4.5 °C above natural standard climate) exhibit higher expression levels of Neuropeptide Y (NPY) and lower expression levels of Cholecystokinin (CCK) in the telencephalon. These results provide insights into the endocrine regulation of appetite in tambaqui under climate change, contributing to the understanding of its impact on both wild and farmed fish populations.

Laske et al. (2023) investigated the effects of climate change on the forage fish Ninespine Stickleback Pungitius pungitius (Linnaeus, 1758) and mercury accumulation increasing under climate change in Arctic lakes, revealing complex interactions between water temperature, fish growth, and prey characteristics. The study emphasised the significance of diet-dependent responses and the potential implications for mercury accumulation in fish under varying climate conditions in Arctic freshwater systems. As expected, warmer temperatures increased annual fish growth, but growth rates and Hg accumulation were heavily influenced by diet. Compared to current growth rates of 0.3 g·y-1, fish growth increased by at least 200% for those consuming energy-dense benthic prey and decreased by at least 40% for those consuming pelagic prey.

White and Wahl's (2020) study of largemouth bass (Micropterus salmoides) revealed similar growth in response to increasing heat. The study compared fish from ambient and external lakes and concluded that largemouth bass can mitigate the sub-lethal effects of warming by altering physiological processes that reduce the impact of warming on aerobic scope, and these changes are

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generationally transient, but changes in maximum thermal tolerance in response to warming are limited to phenotypic plasticity.

Another study on sardines (Sardina pilchardus) found that warmer temperatures in planktonic fish being prey can reduce sardine group size due to decreased food intake (Queiros et al., 2024). Their findings suggest that declines in prey size, combined with warming, could influence energy allocation to life-history traits in wild populations. This bottom-up effect may explain some of the shrinking and declining conditions of many small pelagic fish populations, as well as contribute to the shrinking of other fish species throughout the marine food web. Understanding how declines in prey size can interact with warming to affect consumers is critical for projecting the effects of ongoing anthropogenic global change on marine fauna.

Focusing on three gravel-spawning fish species (brown trout (Salmo trutta L.), common nase (Chondrostoma nasus L.) and Danube salmon (Hucho hucho L.), the mesocosm study by Wild et al. (2023) exposed the synergistic effects of warming, fine sediment (inorganic particles less than 2 mm in diameter), and low-flow on hatching success and embryonic development. Fine sediment had the most significant negative impact, and when combined with other stressors, synergistic responses occurred with species-specific susceptibilities. The study underscores the importance of assessing multiple stressors to understand the complex and species-dependent effects of climate change on freshwater ecosystems.

The investigation into reed biomass dynamics under different nutrient levels presents an opportunity to delve into the long-term effects of nutrient enrichment on plant communities. Examining the resilience of reed ecosystems to sustained nutrient enrichment and its implications for ecosystem stability could be a valuable research trend (Cole et al., 2021). While the study by Strandberg et al. (2022) highlights the influence of nutrient treatment on phytoplankton EPA and DHA concentrations, there's a potential research gap in understanding the ecological implications of changes in polyunsaturated fatty acids (PUFA) for higher trophic levels. Investigating the cascading effects on zooplankton and, ultimately, on fish could provide a more comprehensive picture. The study on tambaqui fish demonstrates the unstable effects of climate change on gene expression related to appetite regulation (Carmo et al., 2023).

A research gap may exist in extending the Carmo et al. (2023) investigation to explore the broader physiological and behavioral impacts on fish populations, considering factors beyond appetite regulation. The study on forage fish mercury accumulation in Arctic lakes highlights the complexity of interactions influenced by climate change (Laske et al., 2023). A potential research gap could involve a more detailed examination of the mechanisms driving the observed diet-dependent responses, including the role of different prey species in mercury accumulation. The mesocosm study on gravel-spawning fish identifies the synergistic effects of multiple stressors. A research gap may involve exploring the long-term consequences of these interactions on the overall health and sustainability of freshwater ecosystems (Wild et al., 2023). Additionally, understanding the potential adaptive responses of different fish species to changing conditions could be valuable. Addressing these potential research gaps could contribute to a more comprehensive understanding of the ecological consequences of climate change and help guide future conservation and management strategies.

3.2. Microbes and Climate Change Combination Impacts in Fish and Aquatic Ecosystems

3.2.1. Microbial Threat to Fish

Adamek et al. (2023) present the connection between climate change, extreme weather, and salmonid susceptibility to a new viral pathogen, Tilapia lake virus (TiLV) in a range of water temperatures which can be reached during summer heatwaves in Continental Europe. Disease outbreaks caused by pathogens are directly correlated with ambient temperature in poikilothermic animals such as fish. The pathogen may potentially infect hosts as a result of their thermal stress and habitat loss brought on by rising temperatures, according to the study's hypothesis. The virus shows strong resistance, indicating the possibility of pathogenic effects in salmonids, especially in relation

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to anthropogenic activities and climate change, even though cohabitation reduces the susceptibility of rainbow and brown trout to TiLV.

Two significant recent studies that highlighted the emerging patterns of microbiological threats were picked. Both of them discuss microbial threats to aquatic ecosystems and animal health, emphasizing negative impacts on fish and economic implications. Davidovich et al. (2023) emphasise the economic significance of the introduced parasite, focusing on specific challenges such as biological invasion, while Elegendy et al. (2023) address the need for effective management strategies to protect commercial marine fisheries from marine pollution-induced bacterial diseases.

Davidovich et al. (2023) discuss the threat of Amirthalingamia macracantha, an African parasite now found in farmed fish liver, which has recently established itself in the Middle East, possibly as a result of the migration of its ultimate hosts, great cormorants *Phalacrocorax carbo* (Linnaeus, 1758). The parasite poses economic risks to aquaculture, particularly affecting the organs of the farmed and wild fish, including tilapia. This study highlights the rapid spread of the parasite in both migratory and non-migratory birds and the potential for further dissemination to other areas. The discussion of the introduced parasite is thorough, emphasizing its economic impact on aquaculture and potential spread to fish through bird migration. The inclusion of histopathological examination results adds scientific rigor. However, more details on the broader ecological consequences beyond economic impact would enhance the overall understanding.

Elegendy et al. (2023), on the other hand, concentrate on the problems caused by anthropogenic marine pollution, which causes bacterial disease outbreaks that reduce marine fish production. The study identifies various marine pollutants, including oil, heavy metals, and agrochemicals, that primarily cause Gram-negative bacteria such as vibrio spp, pseudomonas spp, and aeromonas spp, emphasising the link between pollution and bacterial diseases, with those gram-negative bacteria being the most common culprits. The study calls for effective management strategies and regulations to mitigate the effects of marine pollutants on aquatic animal health, supporting the sustainability of commercial marine fisheries. The study effectively outlines the diverse range of marine pollutants affecting fish health, particularly underlining the connection between pollution and bacterial diseases. The request for effective management strategies is commendable. However, the work could benefit from specific examples or case studies to illustrate the severity of the issues raised.

Mortality episodes have affected juvenile smallmouth bass (Micropterus dolomieu) in several river systems in Pennsylvania since 2005 (Boonthai et al., 2018). Several laboratory tests were conducted by Boonthai et al. (2018) to determine whether the largemouth bass virus (Ranavirus, Iridoviridae) could be the cause of these events. The results showed that juvenile smallmouth bass Micropterus dolomieu (Lacépède, 1802) infected with the largemouth bass virus in experiments had mortality as well as internal and external clinical symptoms resembling those observed during die-offs. The fish that were infected displayed multifocal necrosis in their kidneys, liver, spleen, and mesenteric fat when examined under a microscope. Rare cases of panuveitis, keratitis, severe ulcerative dermatitis, and necrotizing myositis were also observed in fish exposed to immersion challenges. More smallmouth bass infected with the largemouth bass virus died at 28 °C than at 23 or 11 °C. Smallmouth bass that had previously contracted the largemouth bass virus experienced a marked increase in mortality upon co-infection with Flavobacterium columnare at 28 °C. Fish seem to be particularly susceptible to Aeromonas salmonicida when the water temperature is below 23 °C. Although juvenile smallmouth bass may suffer greatly from co-infection with both A. salmonicida and the largemouth bass virus, in field settings, it is highly unlikely that these two pathogens will work in concert because their optimal temperatures are 7–10 °C apart. Finally, based on the total amount of data collected for this study, it can be concluded that the largemouth bass virus may be the cause of the juvenile smallmouth bass mortality episodes that are seen in waters with relatively high temperatures due to climate change.

Milan et al. (2023) investigated the combined effects of climate change and vibrio infections on Manila clam (Ruditapes philippinarum) in the Venice lagoon on a long term period. The Venice lagoon is an ecosystem in which tidal barriers and anthropogenic activity present similar impacts to climate change, so studying its clam populations is very accurate in describing the combined effects. The disruption of clam immune response, the spread of Vibrio spp., and the up-regulation of molecular pathways involved in xenobiotic metabolism were among the most significant findings, implying major environmental stressors affecting clams farmed in areas leading to high mortality rates.

3.2.2. Microbial Infections Under Climate Change Interactions with Fish Physiology

Mesocosm experiments on (commercial) fish infected with various microbes, combined with changes to one or more aquatic ecological parameters, (e.g., salinity, temperature, nutrients) are currently trending in laboratory research. Their main theory is that fish physiology is impacted the way fish microbes populations react, both quantitatively and qualitatively, as a result of aquatic climate change (Segaran et al., 2023; Suzzi et al., 2023; Peres Costa et al., 2020).

Segaran et al. (2023) lengthy study emphasize the pivotal role of microbes in the biosphere for over 3 billion years and their significant impact on climate change, particularly in the marine environment. The study uses scientometric methods to analyze 2767 documents, revealing exponential growth in microbial-related research, with key keywords such as "microbial diversity" and "ocean acidification". The study employs a scientometric approach to map research trends in microbial-related climate change studies. It effectively identifies influential clusters like "coral microbiome" and "hypoxic zone." However, the review lacks specific findings or insights derived from the analyzed literature, making it challenging to evaluate the depth of the study's contributions.

Peres Costa et al. (2020) study characterizes the foodborne microbes of Gilthead sea bream Sparus aurata (Linnaeus, 1758) and Sea bass Dicentrarchus labrax (Linnaeus, 1758) in estuarine and marine ecosystems in Andalusia, Spain. Microbial analysis reveals no significant differences between fish types, but higher concentrations of *Enterobacteriaceae*, total coliforms and for *Staphylococcus* spp. coagulase + in viscera in estuaries. The study emphasizes the importance of preventing microbiological contamination in estuary production systems for product quality and safety. It also provides valuable insights into the microbiological quality of fish in estuarine ecosystems, highlighting the significance of preventing contamination when the climate change will alter the aquatic salinity. However, it could benefit from more detailed discussions on the implications of the findings for fisheries management and potential interventions to improve water quality in estuarine production systems.

Contrary to Peres Costa et al. (2020), Suzzi et al. (2023) discuss the impact of increasing marine water temperatures, particularly in eastern Australian estuaries, on the abundance and virulence of pathogenic Vibrionaceae. The study uses molecular techniques to analyze microbial communities in fish gut and seawater, revealing dysbiosis in fish guts under thermal stress and potential future risks due to pathogenic Vibrionaceae. This study significantly contributes to understanding the dynamics of emerging pathogens in wild aquatic organisms in the context of rapid warming. The use of molecular techniques adds depth to the analysis, and the identification of opportunistic pathogen increases in estuarine fish provides valuable insights. However, further exploration of the broader ecological implications and potential mitigation strategies would enhance the study's impact.

In addition to microbial interactions in fish, these combined findings show that microbial interactions are important for both long-term planetary processes and acute ecological reactions to climate change. Estuarine ecosystems, crucial for fish production, face microbial challenges that vary with anatomical parts and geographical locations. Rising sea temperatures exacerbate microbial issues, impacting fish gut microbial communities and potentially leading to the proliferation of pathogenic species. Understanding these microbial interactions is crucial for managing ecosystems, ensuring food safety, and predicting future risks associated with climate change.

4. Discussion and Critical Review

Climate change interactions with aquatic ecosystems have multiple, complex, and overlapping effects on floral and faunal biodiversity. This general conclusion is evident in all aspects of the

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relevant research, including field-based measurements, data analysis from field collections, laboratory experiments, and ecological modelling synthesis. The methodology used to study climate change interactions with fish fauna ranges from field measurements to laboratory experimental observations, as well as theoretical ones, such as spatiotemporal data mining and metadata analysis, which lead to modelling approaches for the current and future states.

In terms of modelling, there is a wide range of software options, with LCA being the most popular. LCA modelling is an effective instrument for aquaculture research, providing information on the ecological impact and sustainability of the farmed product. Climate change is used to predict ecological impacts and product input costs in a variety of scenarios. Even though LCA is a commonly used tool in aquaculture, it requires better inputs to produce reliable results. LCA, like all modelling tools, has limitations in some of its inputs and outputs, as it relies on constants whose future behaviour is uncertain due to climate change unpredictable and versatile impacts, necessitating the use of focused tools.

Heavy metal concentration is critical for the health of aquatic ecosystems and fish, and their impact can be quantified using models. In the study conducted by Laske et al. (2023), bioenergetic models were used to assess fish growth in relation to mercury accumulation, and this approach is highly recommended because it is inexpensive and accurate for predicting metal and nutrient concentrations under climate change scenarios. Some additional recommendations for bioenergetics modelling include combining it with laboratory testing of fish food intake and altering the oxygen concentration, which is known to affect both nutrient concentration and oxygen levels.

The literature review found that both wild and farmed fish are impacted by climate change interactions. Some key implications are that native species are harmed by rising temperatures in their natural habitats, whereas invading fish benefit from this rise, and this mixed community of both alien and native species, in addition to severe biodiversity alteration, may result in new hybrid production of cross pollinated fish from the same family or genus. As both native and invasive species seek suitable habitats, competition for resources such as food, breeding sites, and shelter could grow. This competition can cause additional stress on native species, potentially leading to population declines. Invasive species can disrupt natural predator-prey dynamics. For example, if an invasive predator enters a region, it may target native prey species that are not prepared to deal with the new threat, resulting in population declines or even local extinctions.

On the other hand, invasive prey species may outcompete native prey, reducing food sources for native predators and potentially threatening their reproduction and survival. Invasive species have the potential to introduce new diseases or parasites into native populations, as they may have evolved resistance to these pathogens in their native range, causing health problems for native species, further affecting their populations. Native and invasive species can interbreed, resulting in hybridization, which can cause genetic changes in native populations, affecting their ability to adapt to changing environmental conditions. These adverse impacts were noted in the introduction of the predatory northern pike (Esox lucius) into western North America, where it has negatively affected native fish populations (Washington & Harvey, 2011; Dunker at al., 2020). Another example is the introduction of the Nile perch (Lates niloticus) in Lake Victoria, Africa, which led to significant ecological changes and declines in native cichlid (Cichlidae) fish species (Achieng, 2016). Conservation efforts should involve local communities, researchers, and policymakers. Engaging communities in monitoring and management initiatives can improve the effectiveness of conservation efforts. These are critical parameters to investigate further, requiring an extensive, holistic and adaptive approach that takes into account ecological, social, and economic factors.

Most of the studies in this review found that climate change affects both marine and freshwater fish. This study clearly emphasised farmed and commercial fish due to the extensive research conducted and the significant role fisheries play in socioeconomic aspects. Some key findings from the review include greenhouse gas emissions have greater impact on freshwater fish diversity, declining freshwater biodiversity due to land cover change, man made structures raising the freshwater surface level (e.g., barrages), and estuaries having higher pathogenic microbial

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concentrations. Because of their shallow waters and limited areas, fluvial and lake ecosystems are more vulnerable to the effects of climate change than the hectic marine ecosystem. Freshwater fish have to deal with more acute and diverse combined climatic parameters, such as the water temperature, the nutrient levels, the microbial load, oxygen concentration, etc, because the water mass is considerably less than the marine and ever-moving, causing fish to constantly migrate and consume energy, as well as being infected with diseases that thrive in this changing ecosystems.

It has been proven that in freshwater environments subject to climate change, fish undergo alterations to their ordinary biological systems, leading to detrimental effects on their development, respiratory, digestive, and circulatory systems. The study's findings show that the major organs of fish, including the brain, heart, gills, liver, kidneys, and others, are impacted. Most of these modifications have been seen in the osmoregulative processes in both freshwater and marine fish, which can result in abnormal growth and increased susceptibility to pathogen infections because osmoregulation and immune systems are closely related. There is also a lack of solid knowledge about reproduction rates and juvenile growth, and more research in this area is required to better understand future fish reproduction and early stage structure under climate change interactions, allowing aquaculture to prepare and adjust to the new situation.

The effects of climate change on marine environments have been thoroughly tested over the years, both theoretically (modelling) and practically (lab experiments and time series sampling). Contemporary research indicates a trend toward comparing fish biology to ecological factors in marine surface, water column, and sediments. The concentration of nutrients and their impact on fish individuals and groups are common parameters that interact in all sea layers. It is expected that the nutrient levels at the sea surface will decline as a result of climate change, which will affect surface fish in many aspects due to the variety of factors that function at the water surface and its immediate interaction with the air, such as oxygen intake, temperature changes, and salinity.

Another common factor that interacts in all seawater layers is fish foraging, particularly the dynamics of fish herds. As previously stated, nutrient levels fluctuate, affecting aquatic plant biomass and thus causing problems in fish communities. Future research must focus on phosphorus concentrations because of their potential to increase plant growth in a phenomenon known as eutrophication, which affects fish habitats primarily through oxygen limitation and increased food provision. This suggestion can be strengthened even more by expanding the studies scope beyond local boundaries.

The reproduction activity of fish populations in the context of climate change is a major source of concern for their dynamics and future fate. Current research focuses on two major trends: sand and gravel alterations of the seabed and the effects of ecological factors on the fate of fish reproduction, as well as early stages and juvenile physiology and growth. Climate change on seabed sand and gravel sediments in fish spawning areas has a negative impact on fish fauna because it causes habitat loss and fragmentation for various marine species that depend on these habitats for shelter, feeding, and reproduction. This occurs for a variety of reasons, including increased erosion caused by higher temperatures, storm surges and wave action, which eventually results in seabed disturbance, and acidification of the marine water, which affects organisms living on the sand and gravel seabed, such as shellfish and corals, by weakening their calcium carbonate structures. Rainfall, river flow, and ocean current patterns are altered, affecting sediment transport processes. Changes in sediment supply can influence the distribution and composition of sand and gravel sediments. Based on these interactions, we can investigate the effects of climate change on marine sediment, which serves as the primary habitat for fish reproduction.

Thus, fish species rely on specific substrate types, such as sandy or gravelly seabed, for successful reproduction; changes to these habitats can disrupt spawning behaviour and reduce reproductive success. Rising sea temperatures can affect the timing and success of fish reproduction. Altered nutrient dynamics and shifts in primary productivity can have an impact on the availability of food for larval fish. Adequate food availability during the early life stages is critical for fish larvae survival and growth, and food web disruptions can have significant implications for fish populations

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and reproductive success. Changes in predator species abundance and distribution can have an impact on fish egg and larvae survival, resulting in higher mortality rates and lower overall reproductive success. As previously stated, ocean acidification can weaken the calcium carbonate structures of coral reefs and shellfish beds, which serve as critical spawning grounds for many fish species. The loss of these habitats can limit the availability of suitable spawning sites and disrupt critical reproductive behaviour.

This study additionally revealed a current research trend in which microbial infection and climate change factors on water combine to have a negative impact on fish physiology and growth, influencing all fish biological systems. Microbial load increases rapidly as water temperature and nutrient concentrations rise. This combination, along with the other climate change parameters, causes infected fish populations to change rapidly and randomly, making these studies critical for fisheries and aquaculture research in the future. An emerging concern coming from these studies is the introduction of new microbial communities to water areas as a result of climate change, resulting in previously unknown and unstudied fish infections. The conclusion drawn from these is the need, perhaps urgently, to organise more experiments investigating the combined effects of microbes and climate change on fish in order to gain better and broader understanding.

5. Conclusions

Diverse fish species react to climate change in different ways, with both beneficial and detrimental effects. The mid-term impacts of climate change on fish populations and aquaculture seem more promising overall, with faster growth rates and some advantages. However, long-term forecasts show negative trends that could have an effect on aquaculture and fisheries productivity, particularly in areas that are currently productive. Different scenarios show changes in biomass, with differing effects on important species such as gilthead seabream, Sea bass, striped bass, Tilapia, blue crab, mussels and oysters. Climate change affects food web dynamics and trophic interactions, suggesting possible changes in species dominance and ecological relationships.

Fish that are euryhaline exhibit physiological responses to fluctuating salinities, such as the capacity to adjust for ongoing variations in salinity and a modification in prolactin signalling. Comprehending these physiological reactions is essential for forecasting fish populations' adaptability to various environments. International research highlights the detrimental effects of climate change on fish growth, highlighting the significance of taking temperature variations into account. Studies conducted in specific areas, like estuaries, show how different species react differently to variations in water temperature, which can have an impact on growth rates and foraging habits.

Research that has already been done emphasises the knowledge gaps, which include biases towards particular species, habitat types, and geographical areas. Further research should examine a wider range of species, regions, and ecological contexts in order to gain a deeper understanding of the effects of climate change. The results highlight the significance of adaptive management approaches that take into account both the short- and long-term impacts for aquaculture and fisheries. Maintaining both wild and farmed stocks of fish depends on tracking and reducing the effects of climate change on fish populations. In combination, the findings highlight the intricate and varied ways that fish species are impacted by climate change, underscoring the need for an all-encompassing and flexible approach to fisheries and aquaculture management.

The primary research trend in laboratory climate change testing is the interaction of environmental factors with fish physiology and growth. The research review revealed that aquatic temperature, oxygen concentration, salinity, nutrient concentrations, and Carbon dioxide were the most tested parameters against fish growth and the function of fish biological systems such as the reproductive, digestive, and immune systems. Another current trend in laboratory research involves mesocosm experiments on commercial fish infected with different microbes, coupled with alterations in aquatic ecological parameters like salinity and temperature. The overarching theory posits that fish physiology is influenced both quantitatively and qualitatively by the behavior of fish microbes, particularly in response to aquatic climate change.

Fish microbes' fate and dispersal will be affected by changes in climate-related ecological factors. When combined with the other ecological stressors that are applied in parallel, such as the concentrations of nutrients and oxygen, as well as temperature and salinity, this will negatively affect the physiology and growth of fish. Because of this, it is imperative and crucial that combined studies be conducted in the lab mesocoms.

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