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THE INVISIBLE CRISIS: DISEASES OF FRESHWATER FISH CAUSED BY CLIMATE CHANGE. A REVIEW

Angelica DOBRE[1, 2], Maricel Floricel DIMA[2, 3], Christian STEINBERG[4], Carmen Georgeta NICOLAE[1]

[1]University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, District 1, Bucharest, Romania
[2]Research and Development Institute for Aquatic Ecology Fishing and Aquaculture, 54 Portului Street, Galati, Romania
[3]Faculty of Engineering and Agronomy in Braila, "Dunarea de Jos" University of Galati, 29 Calea Calarașilor Street, 810017, Braila, Romania
[4]Faculty of Life Sciences, Freshwater and Stress Ecology Group, Humboldt Universität ZuBerlin, 12437, Berlin, Germany

Corresponding author email: angelica.dobre85@yahoo.com

Abstract

Climate change poses significant threats to aquatic ecosystems, notably impacting fish health. Rising global temperatures have led to higher water temperatures in freshwater ecosystems, intensifying stress and disease vulnerability in fish populations. This review investigates the role of bacterial pathogens, specifically Aeromonas hydrophila, Edwardsiella tarda, and Flavobacterium columnare, which thrive in warmer aquatic environments. These pathogens exhibit increased virulence under thermal stress, leading to disease outbreaks in fish. The study examines the relationship between climate change, pathogen proliferation, and fish health, emphasizing the critical need for management strategies to mitigate the effects of infectious diseases in aquaculture and natural ecosystems.

***Key words**: Aeromonas hydrophila, Edwardsiella tarda, environmental change, Flavobacterium columnare, pathogens.*

INTRODUCTION

Climate change is an undeniable fact and one of the greatest challenges facing the planet in the 21st century, having a profound impact on all ecosystems, with extreme weather events and increasingly frequent precipitation, more intense heatwaves, and droughts (Stefan & Sinokrot, 1993; IPCC, 2014; Islam et al., 2022). The climate crisis has increased the global average temperature. According to NASA's GISTEMP Team (2024), the last decade of the 20th century and the beginning of the 21st century represent the warmest period in the last 2000 years.

In this context, aquatic ecosystems are extremely vulnerable to temperature fluctuations, and climate change is advancing so rapidly that biodiversity is struggling to adapt, with fish not being an exception. These stress factors affect not only natural waters but also aquaculture farms that depend on water sources from natural environments. Pathogens present in these waters can be transported to aquaculture sites, threatening fish health and increasing the risk of disease outbreaks in farms. Thus, climate change intensifies the dangers for both natural ecosystems and aquaculture.

Water temperature is an essential parameter in determining the health of these ecosystems (Cairns et al., 1975; Dallas, 2009; Zhou et al., 2014), as each fish species has a specific temperature range it can tolerate (Munteanu & Bogatu, 2008), which influences their growth, reproduction, performance, and survival (D'Abramo & Slater, 2019; Islam et al., 2022).

The increase in global temperatures has led to significant changes in aquatic environments, including rising water temperatures in rivers and lakes (Ambrosetti & Barbanti, 1999; Livingstone, 2003), increasing pollutants concentrations. These changes affect not only water quality (Kernan et al., 2011) but also the health of fish and other aquatic organisms (Aadland, 1993), triggering a range of physiological and biological responses. Temperature variations can cause corticosteroid responses (Barton & Peter, 1982; Houghton & Matthews, 1990; Alfonso et al., 2021, 2023), metabolic changes (Munteanu & Bogatu, 2008; Jutfelt, 2020; Volkoff & Rønnestad, 2020), immune responses (Ahmad et al., 2020; Alfonso et al., 2021; Islam et al., 2022), the production of heat shock proteins (Lindquist & Craig, 1988; Arias et al., 2011; Folguera et al., 2011; Dawood et al., 2020; Somero, 2020), and antioxidants (Vinagre et al., 2012; Madeira et al., 2013), as well as fluctuations in haemolymph parameters (Kazmi et al., 2022; Li et al., 2022). Additionally, it contributes to the proliferation of pathogens and the emergence of diseases in fish (Sheikh et al., 2022).

In poikilothermic animals, temperature also modulates the gut microbiota (Wang et al., 2022; Hai et al., 2023; Zhang et al., 2023; Zhao et al., 2023; Kim et al., 2024). As this microflora can be considered as a separate micro-ecosystem that co-regulates important host physiological pathways, the thermal effects on the gut microbiota and the consequences for host susceptibility to pathogens must also be considered. However, the evidence currently available is insufficient to draw general conclusions.

This paper examines the bacteria *Aeromonas hydrophila* (Chester, 1901), *Edwardsiella tarda* (Ewing et al., 1965), and *Flavobacterium columnare* (Bernardet and Grimont, 1989), which significantly impact the health of freshwater fish. These pathogens are commonly found in aquatic ecosystems, and their prevalence has notably increased due to climate change. Each bacterium has distinct virulence factors and pathogenic mechanisms that enable adaptation to stressful conditions like high temperatures and poor water quality.

Extensive research on these bacteria offers valuable insights into the long-term effects of climate change on fish health, emphasizing the need for effective management of these infections in the future. The paper will explore how extreme climatic conditions may drive the emergence and spread of these diseases.

MATERIALS AND METHODS

The paper is a review based on the analysis of published studies in scientific journals, research reports, and other academic resources investigating fish diseases in freshwater ecosystems and the influence of climate change on these diseases. This approach allows for a comprehensive assessment of existing knowledge and provides a basis for identifying research gaps that require further attention.

Using keywords such as "climate change", "freshwater fish", "bacterial infections", "pathogens", "*Aeromonas hydrophila*", "*Edwardsiella tarda*", "*Flavobacterium columnare*", "Flexibacterium", "temperature effects", "fish health", "infectious diseases", "disease outbreaks" and combinations of these terms, relevant studies were identified, including articles published in reputable scientific journals accessible through international databases such as PubMed, Google Scholar, Web of Science, ResearchGate, Springer etc. Additionally, governmental reports and conference papers were included to enrich the analysis of the existing literature.

The studies were selected based on their relevance to the subject of climate change and its impact on fish diseases in freshwater ecosystems in relation to rising water temperatures, fluctuations in chemical parameters. Emphasis was placed on recent studies to ensure the data's timeliness, considering the rapid pace of climate change.

Works addressing marine ecosystems and oceans were excluded, as the focus is on fish in freshwater ecosystems, where the impact of climate change may differ. Additionally, studies that do not directly refer to climate change or diseases caused by pathogens in this context were excluded, ensuring the relevance and specificity of the analysis. Furthermore, studies regarding the effects of low temperatures on fish health were also excluded.

RESULTS AND DISCUSSIONS

Each fish species has a specific temperature range in which its performance is optimal and growth rates are high. Elevated temperatures favour the development and spread of pathogens. Mk (2013) highlighted that rising temperatures in aquatic environments can disrupt ecological balances, leading to species invasions and outbreaks of diseases that were not previously prevalent, with a significant impact on fish health, increasing their vulnerability to stress and diseases. The ability of fish to survive these threats depends on their resistance and tolerance to pathogens (Soares et al., 2017; Cascarano et al., 2021), as well as on the symptoms that manifest in various forms of interaction with one or more pathogens, from the moment of host exposure to the resolution of effects (Casadevall et al., 2000; Stroe et al., 2022).

Studies have demonstrated that in years with high temperatures, the prevalence and intensity of bacterial infections increase (Park et al., 2012; Shapiro & Cowen, 2012; Chiaramonte et al., 2016; Awan et al., 2018; Delalay et al., 2019) as well as parasitic infections (Matvienko et al., 2020; Sheikh et al., 2022; Stroe et al., 2021, 2022;), which is a relevant aspect for understanding how climate change can intensify pressure on fish.

This situation not only threatens the biodiversity and stability of aquatic ecosystems (Munteanu & Bogatu, 2008; Islam et al., 2022; Kazmi et al., 2022), but it can also lead to significant economic losses for fishermen and aquaculturists. Declines in fish populations due to disease outbreaks can lead to reduced catches, affecting food security and income for fishers (Domenici et al., 2019). Additionally, the increased costs associated with disease management and the need for sustainable fishing practices can strain local economies (Samah et al., 2019). Moreover, these diseases represent a risk also for the human population; through their zoonotic characteristics, they can be transmitted from fish or the infected water to consumers (Totoiu et al., 2018).

Bacterial infections

Edwardsiella tarda

Edwardsiella tarda is a Gram-negative bacterium, formerly classified as an Enterobacterium (Ewing et al., 1965) and currently belonging to the family *Hafniaceae.*, an opportunistic pathogen affecting a significant number of fish species in freshwater ecosystems, where it can persist in waters rich in organic matter, causing substantial economic consequences (Xu & Zhang, 2014). Abayneh et al. (2012) isolated the pathogen in several fish species, including Japanese catfish, eels, and other freshwater and marine species, across different regions of the globe.

Jiang et al. (2019) demonstrated that elevated water temperatures significantly impact the metabolism of fish, leading to altered immune responses and increased susceptibility to *Edwardsiella* infections in crucian carp *Carassius carassius* (Linnaeus, 1758). This finding suggests that temperature influences not only pathogen behaviour but also the fish's metabolic and immune responses, creating a feedback loop that can exacerbate infection rates. Alcaide et al. (2006) identified the bacteria in European eels in Spain. Similarly, Meyer and Bullock (1972) reported infections in fish from Arkansas, US. Even Antarctica wasn't spared (Leotta et al., 2009), nor were other animals or humans (Janda & Duman, 2024), indicating that the disease can operate on a wide geographic scale (Park et al., 2012), especially under imbalanced environmental conditions such as poor water quality or significant organic concentrations (Abayneh et al., 2012), particularly those caused by elevated temperatures (Table 1).

Initially considered a single pathogen, recent phylogenetic research has led to its reclassification into multiple species, including *E. piscicida* and *E. anguillarum*, both of which exhibit specific pathogenicity for freshwater fish (Katharios et al., 2019). Munteanu & Bogatu (2008) and Hirai et al. (2015) reported that mortality rates in cases of Edwardsiellosis can reach up to 50%, causing significant losses in fish populations.

E. tarda infects fish through direct contact with contaminated water or by ingestion of the bacteria. The infection leads to septicaemia, affecting vital internal organs such as the liver and spleen. Among its pathogenic mechanisms is the ability to invade host cells and form biofilms, making it resistant to the immune responses of fish (Griffin et al., 2013). The bacterium can also produce toxins that induce necrosis in infected tissues, leading to increased morbidity and mortality in freshwater fish populations.

Climate change and rising water temperatures can amplify the severity of *E. tarda* infections. At higher temperatures, the bacteria accelerate their life cycle, promoting more frequent and intense outbreaks in freshwater habitats (Shao et al., 2015). Fish in these environments are often subjected to thermal stress, compromising their immune response and making them more vulnerable to infection (Volkoff & Rønnestad, 2020). These adverse climatic conditions can contribute to ecological imbalances, facilitating the proliferation of pathogens in environments where elevated temperatures become predominant.

Table 1. Geographic distribution and freshwater fish hosts of *Edwardsiella tarda* in natural environments

Host	**Geographic region**	**Research**
European eel *Anguilla anguilla* (Linnaeus, 1758)	Norway	Abayneh et al. (2012)
Korean catfish *Silurus asotus* (Linnaeus, 1758)	South Korea	
Japanese eel *Anguillus japonica* (Temminck & Schlegel, 1846)	China	
Channel catfish *Ictalurus punctatus* (Rafinesque, 1818)	Arizona, USA	
Crucian carp *Carassius carassius* (Linnaeus, 1758)	China	Jiang et al. (2019)
European eel *Anguilla anguilla* (Linnaeus, 1758)	Spain	Alcaide et al. (2006)
Channel catfish *Ictalurus punctatus* (Rafinesque, 1818)	Arkansas, USA	Meyer & Bullock (1973)
Largemouth black bass *Micropterus salmoides* (Lacepède, 1802)	Florida, USA	White et al. (1973)
Nile Tilapia *Oreochromis niloticus* (Linnaeus, 1758)	Tanzania	Van Damme & Vandepitte (1980)
Nile Tilapia *Oreochromis niloticus* (Linnaeus, 1758)	Zair	
North African Catfish *Clarias gariepinus* (Burchell, 1822)		
Brook trout *Salvelinus fontinalis* (Mitchill, 1814)	-	Uhland et al. (2000)
Channel catfish *Ictalurus punctatus* (Rafinesque, 1818)	Texas, USA	Wyatt et al. (1979)
Nile Tilapia *Oreochromis niloticus* (Linnaeus, 1758)	Egypt	Moustafa et al. (2016)
Carp *Cyprinus carpio* (Linnaeus, 1758)	India	Acharya et al. (2007)
North African Catfish *Clarias gariepinus* (Burchell, 1822)	Egypt	Abo El-Yazeed & Ibrahem (2009)
Nile Tilapia *Oreochromis niloticus* (Linnaeus, 1758)		
African catfish *Clarias gariepinus* (Burchell, 1822)	Ethiopia	Haile & Getahun (2018)

Freshwater fish infected with *E. tarda* often show signs of septicemia, such as hemorrhages, skin lesions, and ulcers. Severe infections can disrupt osmoregulatory balance, affecting respiratory and digestive systems. Observable symptoms include rapid breathing, lethargy, and reduced overall activity, which can have severe consequences for the survival of affected populations (Munteanu & Bogatu, 2008; Park et al., 2012; Jiang et al., 2019).

Diagnosis of the disease is achieved through bacterial cultures, serological tests, molecular methods such as PCR (Abayneh et al., 2012; Griffin et al., 2013), and genomic sequencing analyses (Abayneh et al., 2012; Shao et al., 2015). Furthermore, the isolation and precise identification of *Edwardsiella* species are crucial for appropriate treatment.

Flavobacterium columnare

The columnaris disease is a common myxobacteriosis in freshwater fish, described in over 40 species (Anderson & Conroy, 1969; Munteanu & Bogatu, 2008; Noga, 2010), caused by the opportunistic pathogen *Flavobacterium columnare* (Soriano, 1945), also known as *Flexibacter columnaris* or *Chondrococcus columnaris*. This Gram-negative bacterium is one of the most frequent causes of fish mortality in freshwater habitats, being particularly dangerous under thermal stress and degraded environmental conditions, caused by high temperatures, low dissolved oxygen levels, and elevated concentrations of organic substances and nutrients (Khalil et al., 2015; Mitiku, 2018). Straus et al. (2015) demonstrated that a key factor in the bacterium's pathogenicity is water hardness. The bacteria have a wide geographic distribution, being considered the second most widespread bacterial pathogen after *Edwardsiella* (Hawke & Thune, 1992; Mitiku, 2018).

For instance, Kinnula et al. (2017) found that nutrient levels in the environment significantly influenced the virulence of *F. columnare* in fish, especially at temperatures between 20- 30°C (Munteanu & Bogatu, 2008), with an optimum at 25°C (Declercq et al., 2013). This indicates that as nutrient levels fluctuate due to climate-induced changes, the pathogenicity of certain bacteria may increase, leading to higher infection rates in fish populations. *F. columnare* can infect many different species of wild freshwater fish, including (but not limited to) carp, channel catfish, goldfish, eel, perch, salmonids, and tilapia (Decostere et al., 1998; Figueiredo et al., 2005; Řehulka & Minařík, 2007; Soto et al., 2008; Suomalainen et al., 2009; Morley & Lewis, 2010; Mitiku, 2018). Transmission occurs horizontally through direct contact and skin wounds (Zaki et al., 2016; Mitiku, 2018) and external tissue, producing necrotic lesions and severe ulcers (Attallah, 2015; Dong et al., 201;) as well as changes in the haematological and biochemical parameters of the host (Tripathi et al., 2005; Mitiku, 2018).

Characteristic symptoms include whitish patches on the body (Declercq et al., 2013; Mitiku, 2018), soft tissue degradation, and gill function loss, leading to breathing difficulties and eventual asphyxiation. A significant aspect of the pathogen's development is its ability to form biofilms, which grants it increased resistance in stressful environments and facilitates the bacterium's survival outside the host for extended periods (Cai et al., 2013; Zaki et al., 2016).

The diagnosis of *F. columnare* infection is made through a combination of clinical examination of affected fish and laboratory tests. External symptoms are often the first indicator of the pathogen's presence. However, to confirm the infection, laboratory methods such as isolating the bacterium from skin lesions or gills, followed by morphological and biochemical identification, are used (Mitiku, 2018). Molecular tests like polymerase chain reaction (PCR) are considered the most precise methods for identifying the bacteria at the genetic level (Triyanto & Wakabayashi, 1999; Attallah, 2015; Dong et al., 2016; Zaki et al., 2016; Mitiku, 2018).

Early diagnosis is crucial to prevent the spread of the disease in fish populations. PCR tests allow for the detection of the bacterium even in early stages of infection, before external symptoms become apparent. The use of genetic sequencing techniques has also contributed to understanding regional variations in *F. columnare* strains, which may have important implications for fish disease management in the context of climate change (Sundberg et al., 2016).

Aeromonas hydrophila

Aeromonas hydrophila (Stanier, 1943) is a secondary Gram-negative pathogen, known for causing ulcer disease in freshwater fish species (Figueras et al., 2007; Ottaviani et al., 2011; Semwal et al, 2023), including species such as carp *Cyprinus carpio* (Linnaeus, 1758) and other cyprinids, catfish, tilapia and sturgeons (Matvienko et al., 2020). It is recognized as an opportunistic pathogen for both homeothermic and poikilothermic species (Thomas et al., 2009; Semwal et al., 2023). This opportunistic bacterium causes haemorrhagic septicaemia and severe infections, characterized by extensive skin ulcers (Plumb & Hanson, 2010), tissue necrosis, and high mortality in affected populations (Austin & Austin, 2016). The disease is particularly severe in natural aquatic environments where water quality is compromised (Pianetti et al, 2008; Casabianca et al., 2015; Jahid et al., 2015; Semwal et al, 2023), and elevated temperatures play an important role in exacerbating these issues. This has been observed in freshwater environments globally (Igbinosa et al., 2012), as bacteria increase their replication rate and secrete more toxins.

Moreover, due to its zoonotic nature (Awan et al., 2018), *A. hydrophila* can be transmitted between animals and humans (Janda and Abbott, 2010; Ottaviani et al, 2011; Semwal et al., 2023), affecting not only fish but also other species (Igbinosa et al., 2012; Austin & Austin, 2016; Xu et al., 2023). Higher temperatures favor the proliferation of *A. hydrophila*, accelerate its life cycle, and increase its virulence, leading to more frequent and severe outbreaks (Austin & Austin, 2016; Awan et al., 2018). Rasmussen-Ivy et al. (2016) demonstrated that *A. hydrophila* becomes much more virulent under elevated temperatures, around 40°C, while Semwal et al. (2023) report the bacterium's ability to survive even at 45°C, with an optimal growth range between 22-32°C. Fish exposed to *Aeromonas* in these conditions are more prone to septicaemia and mortality (Beaz-Hidalgo & Figueras, 2013).

Environmental changes can increase the genetic adaptability of these pathogens, leading to the emergence of new strains (Shimizu, 2014; Awan et al, 2018). These strains may have different virulence and may respond differently to the antibiotics used in disease management. Matvienko et al. (2020) observed a high incidence of bacterial infections in freshwater species during hot summers, with 25%, predominantly of the bacterium *Aeromonas* at 28%, alongside other bacteria such as *Flavobacterium* and *Edwardsiella*.

A. hydrophila is considered an efficient biomarker of a polluted or stressed aquatic environment (Leung et al., 1995; Semwal et al, 2023). Clinical symptoms of the disease are observed in water temperatures above 22°C, which is why bacterial hemorrhagic septicemia (BHS) is considered a summer disease (Munteanu & Bogatu, 2008). The pathogenicity of this bacterium lies in its ability to form biofilms, which allow it to invade host tissues (Samal et al, 2014; Jahid et al., 2015; Semwal et al., 2023; Xu et al., 2023) and increase its antibiotic resistance (Krovacek et al., 1989; Vivekanandhan et al., 2002; Sreedharan et al., 2012; Sudheesh et al., 2012; Semwal et al., 2023). Significant changes occur at the level of biochemical parameters and catalytic concentrations in infected fish (Řehulka, 2002).

The diagnosis of *A. hydrophila* infection is carried out through standard laboratory methods, such as isolating the bacterium on selective culture media and identification through PCR (Igbinosa et al., 2012; Sreedharan et al., 2012; Semwal et al., 2023). PCR is used for the rapid and accurate detection of the bacterium in affected tissues (Austin & Austin, 2016), being one of the primary diagnostic methods for monitoring ulcer disease. In addition, genetic sequencing is occasionally applied in research studies to analyse the genetic diversity of *A. hydrophila* strains and to monitor the evolution of the pathogen in varied environmental conditions (Sreedharan et al., 2012).

Thus, climate change, with a focus on warming freshwater ecosystems and extreme environmental fluctuations, directly impacts the severity and frequency of *A. hydrophila* infections. This phenomenon requires constant monitoring and the implementation of more rigorous preventive and diagnostic measures to protect aquatic ecosystems and fish populations.

CONCLUSIONS

Climate change, particularly increasing global temperatures, has exacerbated disease outbreaks in freshwater ecosystems, severely affecting fish health. Elevated water temperatures favour the proliferation of bacterial pathogens, including *Aeromonas hydrophila, Edwardsiella tarda, and Flavobacterium columnare*, which have adapted to survive and thrive under thermal stress.

The thermal tolerance of these pathogens allows them to exploit stressed fish populations, leading to higher mortality rates.

Disease outbreaks not only threaten biodiversity but also have severe economic repercussions for aquaculture industries. Increased susceptibility of fish to pathogens under changing environmental conditions can lead to reduced fish stocks, decreased yields, and higher management costs for disease prevention.

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