Review Article

An overview of climate change and prevalence of bacterial diseases in salmonid aquaculture

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Abstract

Food fish farming is regarded as one of the most important sectors of the aquaculture industry. Salmon farming is a major contributor to the growth of the aquaculture sector. Climate change is predicted to have a complex impact on aquatic ecosystems, including fisheries and aquaculture. Climate change can cause a fluctuation in water temperature of rivers, lakes, seas, and oceans. This can change the pattern of ocean currents and marine productivity to be redistributed, especially to higher latitudes, and reduce the global concentration of phytoplanktons, increasing ocean acidity, creating deoxygenated zones, and inducing episodic shocks to marine systems. However, the impact of climate change on fish health is not limited to the physical changes in the environment. A change in climate can also influence the incidence of infectious diseases by shortening generation times and/or increasing the survival rates of the pathogenic agents, improving disease transmission, and enhancing the host's susceptibility to the pathogens. The actual impact of climate change on infectious diseases, particularly those caused by bacterial agents, is not fully understood in both wild and captured fish species. This review addressed the impact of climate change on outbreaks of salmonid bacterial diseases and discuss the present gaps.

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Introduction

Food fish farming is regarded as one of the most important sectors of the aquaculture industry (Rahmati-Holasoo *et al.,* 2021, 2022; Ziafati Kafi *et al.,* 2022), with a significant portion of

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global aquaculture production dedicated to food products worldwide. Salmonids represent the third group of farmed fish species, following cyprinids and tilapines (FAO, 2019; Lulijwa *et al.,* 2022). Salmon farming is a major contributor to the growth of the aquaculture sector (FAO, 2014; Lulijwa *et al.,* 2022). As aquaculture spread, new categories emerged, including ecotoxicology (Chen *et al.,* 2020), temperature tolerance (Wade *et al.,* 2019; Cheung and Frölicher, 2020), and health and disease (Brosnahan *et al.,* 2019). Climate change, as a globally significant issue, is expected to have a significant impact on aquatic ecosystems, particularly on fisheries and aquaculture activities. The change in the global climate can significantly affect the patterns of ocean currents, causing a remarkable change in the sea's productivity, especially at higher latitudes. For instance, a decrease or increase in the phytoplankton concentration, an increase in the ocean acidity, and a fluctuation in the oxygen level are all consequences of climate changes in aquatic ecosystems (Butler, 2016; Cheung *et al.,* 2021; Galappaththi *et al.,* 2022). In addition to the physical changes in the environment, climate change can affect the health criteria of aquatic organisms via alterations in pathogen characteristics. Increasing in the temperature of freshwater can have a direct impact on fish pathogens by changing their biological processes or a secondary impact by modifying the distribution and quantity of the fish that are affected (Chiaramonte *et al.,* 2016). A higher fluctuation in water temperature can seriously affect the load of potentially harmful indigenous and exogenous microbiota of aquatic organisms, including fish. This can facilitate the localization, multiplication, and penetration of these microbes into fish tissues, causing mass morbidity and mortality (Marcogliese, 2008).

In other words, increases in the ambient temperature speed up the proliferation of some pathogenic agents, such as bacteria and exacerbates disease outbreaks (Chiaramonte *et al.,* 2016). Although a vast range of bacteria are the most prevalent infectious agents in aquaculture (Palmeiro and Roberts, 2013; Marandi and Rahmati-Holasoo, 2021), the actual impact of climate change on bacterial diseases is not fully understood in both wild and captured fish species (Abirami *et al.,* 2021). This review addressed the impact of climate change on outbreaks of salmonid bacterial diseases and discussed the present gaps.

Climate change and disease outbreaks by Gram-negative bacteria

Yersinia ruckeri

Yersinia ruckeri is the causative agent of yersiniosis, a systemic disease primarily affecting farm-reared trout (*Oncorhynchus mykiss*) that is considered a significant disease in various fish species both in temperate and cold-water aquaculture of freshwater and marine environments. *Y. ruckeri* is known as one of the aquatic bacterial flora in aquatic ecosystems and is the cause of economic losses in many countries, including Canada, Switzerland, Denmark, Great Britain, and Iran

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(Soltani *et al.,* 2014, 2016; Taheri-Mirghaed *et al.,* 2018). Although the disease occurs in various fish species, rainbow trout is the most susceptible species to *Y. ruckeri*. With the exception of salmonid species, the bacterium can invade many other non-salmonid species from the families of Cyprinidae, Acipenseridae, Ictaluridae, and Anguillidae (Pajdak-Czaus *et al.,* 2019).

Y. ruckeri can grow at temperatures ranging from 9 to 37 °C, with an optimal growth occurring between 22 and 25 °C. In salmonids, the disease becomes more serious and causes higher morbidity and mortality when the water temperature is increased to above 15 °C, which is a stressful condition for the fish. Therefore, disease outbreaks can be increased in salmonid aquaculture by changes in the global climate, especially in the northern hemisphere, where nowadays the water temperature increases during the summer season (Kumar *et al.,* 2015). Although most bacterial isolates incubated at 37 °C are non-virulent to fish, biotype II strains can cause disease in both temperate and tropical fish species, thus making the disease as a re-emerging bacterial disease (Wrobel *et al.,* 2019). The severity of the outbreaks depends on some virulence factors of the bacterial strains and the degree of environmental stress. In the risk framework, which was developed to investigate the impact of climate change on disease emergence in freshwater fish in the United Kingdom, it was shown that fish yersiniosis was likely to be more prevalent and more difficult to control with a global warming condition (Marcos- López *et al.,* 2010).

Aeromonas salmonicida

*Aeromonas salmonicida*is is the causative agent of furunculosis in fish (Soto-Dávila *et al.,* 2022) and so far five subspecies, *A. salmonicida salmonicida, A. salmonidia achromogenes, A. salmonicida masoucida, A. salmonicida smithia,* and *A. salmonicida pectinolytica,* have been detected as the cause of disease in both salmonid and non-salmonid species (Romstad *et al.,* 2012; Schwenteit *et al.,* 2013). Some new atypical strains causing severe mortality in farmed salmonids have also been reported (Vasquez *et al.,* 2022).

The optimum growth temperature for *A. salmonicida* is reported at 22-25 °C, and most strains are unable to grow at 37°C (Woo and Cipriano, 2017). However, recent reports have demonstrated the existence of some strains able to grow at 37°C and even cause infections in immune-compromised humans (Tewari *et al.,* 2014). Thus, by increasing water temperature, these new, higher-temperature-tolerated isolates can become more prevalent in aquatic ecosystems. This is especially true as reports regarding furunculosis in temperate and tropical fish species are becoming abundant. Thus, it is more likely that the disease is latent in cooler environments and turns into an active stage in warm environments, as the disease outbreaks are more common in summer months. In salmonids, the bacterial isolates prefer water temperatures of 16 °C or higher, which is a stressor factor for the cold-water fish family; thus, with global warming, disease outbreaks can become more serious in the spring and autumn.

Flavobacterium columnare

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F. columnare as the causative agent of freshwater columnaris disease in many fish species in both tropical and temperate environments (Patra *et al.,* 2016) is categorised into five genomovars that are apparently geographically dependent (Kayansamruaj *et al.,* 2017), but with a worldwide distribution. The pathogen can infect a wide range of fish, including Salmonidae, Cyprinidae, Anguillidae, Ictaluridae, and Acipenseridae (Declercq *et al.,* 2015; Verma *et al.,* 2015; Lange *et al.,* 2021).

The disease outbreak is highly temperature-dependent, thus, more incidences of disease outbreaks are expected at higher water temperatures as the optimal temperature of *F. columnare* is varied from 25 °C (Cain and LaFrentz, 2007) to 37 °C (Bernardet, 1989), with the shortest generation times of 2 hours at 30 °C, 3.7 hours at 20 °C, 4.4 hours at 15 °C, and 34 hours at 4°C (Soltani and Burke, 1995). If fish are affected by the virulent strains of the bacterium at 20-35 °C, rapid mortality can occur without any clinical signs (Soltani *et al.,* 1996). Thus, the disease outbreaks and mortality by *F. cloumnare* are associated with seasons when water temperature rises (Evenhuis *et al.,* 2014), and temperatures above 18°C promote columnaris epidemics with high mortalities (Runtuvuori-Salmela *et al.,* 2022). The effect of higher temperatures on columnaris disease is due to the shortening of the bacterial generation time, increasing the adhesion capacity of the pathogen in fish tissues, increasing the host susceptibility to columnaris disease, and enhancing the chances of bacterial initiation and colonization (Suomalainen *et al.,* 2006; Farmer *et al.,* 2021). It has been suggested that global warming has an impact on the increased prevalence of columnaris disease in countries such as Finland, where the water temperature has increased by approximately 2-3°C over a twenty-year period (Shoemaker *et al.,* 2012).

Flavobacterium johnsoniae

F. johnsoniae, formerly known as *Cytophaga johnsonae*, the causative agent of the false columnaris (Soltani et al, 1994), is a suitable model organism for studying gliding motility function, gene regulation, and biochemistry (McBride *et al.,* 2009).

Although *F. johnsoniae* is generally regarded as an opportunistic fish pathogen, it has been able to induce disease in barramundi fish when the water temperature was lowered from 28°C to 20°C (Soltani *et al.,* 1994). During the five-year surveillance of fin-rot problems in Norwegian salmonid fish farms, the bacterium was the most dominant etiological agent. Therefore, with the increasing temperatures in aquatic ecosystems, the infection by this bacterium can become more prevalent in both freshwater and brackish environments.

Flavobacterium psychrophilum

F. psychrophilum, a filamentous Gram-negative bacterium, is the causative agent of the systemic disease called bacterial cold-water disease (also called rainbow trout fry syndrome) (Harrison *et al.,* 2022). The disease has been frequently reported in wild and cultured salmonids as well as non-salmonids.

Most of the recovered bacterial isolates can grow at temperatures ranging from 4-23°C,

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with an optimum growth temperature of 12-15 °C. However, it cannot survive at 25 °C or higher (Oplinger and Wagner, 2013; Tenma *et al.,* 2021). The disease predominantly occurs at 16 °C but is generally more prevalent and severe at 10 °C (Starliper, 2011). Thus, bacterial cold-water disease can be prevalent in the northern or southern hemispheres where the iced mountains are thawing due to climate change.

Flavobacterium branchiophilum

F. branchiophilum, an ubiquitous bacterium in the freshwater environment, is the causative agent of bacterial gill disease (BGD) (Dar *et al.,* 2022). Many juvenile freshwater fish species are susceptible to BGD (Plumb and Hanson 2010), but cultured salmonids, mainly rainbow and brook trout, are the most severely affected species. BGD has been reported to have a worldwide distribution, ranging from North America and Europe to Japan, and water supply, sediments, and pathogen-carrying fish are thought to be the reservoirs of the bacteria.

The bacterium generally grows at 4 to 23 °C, depending on the bacterial strain. The optimum growth of the bacteria is also varied among different strains and has been reported to be in the range of 15-19 °C (Uddin *et al.,* 2008). Although the virulence of *F. branchiophilum* is not as severe as that of *F. columnare* or *F. psychrophilum*, it is still one of the important pathogens that affect salmonid aquaculture industries.

As a result of climate change, heavy rainfall may occur, causing disturbance in fine particle-size sediments in the water supply pipes or in the spring collection basin. These sediments can enter holding tanks, and, as a result, BGD outbreaks may occur within 1-2 days. Also, seasonality may have an influence on BGD occurrence since the majority of outbreaks happen in the spring, which coincides with an increase and/or fluctuation in water temperatures. However, the relationship between the environment, in particular the effect of climate change, and the occurrence of the disease warrants further studies.

Tenacibaculum maritimum

T. maritimum, the cause of an ulcerative disease of marine fish, is an opportunistic bacterium that commonly invades the gills and skin of susceptible fish (Valdes *et al.,* 2021). Although an increase in the population of this agent has been observed with gill disease (Ruane *et al.,* 2013), the relationship between these two factors has not yet been discovered. The pathogen has been reported in many different marine fish species in Japan, Europe, Australia, the United States, Chile, and Canada (Frisch *et al.,* 2018; Bateman *et al.,* 2022). Other species of *Tenacibaculum* that have been implicated as salmonid pathogens and cause similar disease complications are *T. finnmarkense* (Småge *et al.,* 2016, 2017) and *T. dicentrarchi* (Wade & Weber, 2020). The significance and emergence of tenacibaculosis have been noted recently in a variety of cage-cultured marine fishes, including salmonids of different ages (Toranzo *et al.,* 2005).

The growth temperature of the pathogen is 15-35 °C with an optimum at 30 °C (Avendaño-Herrera *et al.,* 2006). Depending on the type of bacterial strain, environmental stressors such as high water temperature (> 15 °C) are usually a

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risk factor for the disease occurrence (Downes *et al.,* 2018; Frisch *et al.,* 2018). Other risk factors, including high salinity (30 ppt), increased ammonia, and physical or toxic damage, can all be stimulated by the change in global climate making fish become more susceptible to such bacterial disease (Mitchell and Rodger, 2011).

Motile Aeromonads

Various species of motile *Aeromonas* species are the causative agents of motile *Aeromonas* septicaemia (Rahman *et al.,* 2022), among which *Aeromonas hydrophila*, *A. veroni, A. sobria*, and *A. dhakensis* are more prevalent as the cause of disease in finfish (Carriero *et al.,* 2016; Nhinh *et al.,* 2021). However, *A. hydrophila* is the most serious pathogen, and it caused bacterial septicaemia in various fish species, including salmonids (Eftekharmanavi *et al.,* 2020). It is also a serious pathogen for amphibians, reptiles, and humans (Dias *et al.,* 2016; Woo *et al.,* 2022). The severity of the disease is often stress-dependent particularly under conditions of water temperature fluctuations leading to higher temperatures and poor water quality conditions (Kim *et al.,* 2021).

The pathogen can be isolated from various water sources, including brackish water, freshwater, estuaries, seawater, chlorinated water, sludge, sewage, and aquatic sediments, particularly during the warm months of the year.

Depending on the species, they prefer temperatures of 22-28 °C or 35-37 °C and salinity up to 6% NaCl for a better growth and multiplication (Joseph and Carnahan, 1994). An increase in water temperature can influence the host's susceptibility and is linked with the production of bacterial virulent factors such as cytotoxins and haemolysins, hence, the virulence factors seem to be temperature-dependent. For instance, clinical strains of *A. hydrophila* can grow at temperatures higher than 28 °C, but when the temperature is raised to 37 °C, the protease activity of the bacterium decreases while the cytotoxin and haemolysin activities increase (Rasmussen-Ivey *et al.,* 2016). From a climate change point of view, outbreaks of motile *Aeromonas* septicaemia in salmon farms are notable, as with an increase in water temperature, more morbidity and mortality can be anticipated.

***Vibrio* spp.**

Vibriosis is caused by certain *Vibrio* and *Photobacterium* species, which are important pathogens in marine aquatic environments. These agents are pathogenic in wild and farmed aquatic animals, including fish, crustaceans, molluscs, corals, and rotifers (Gomez-Gil *et al.,* 2014). About 60% of heterotrophic bacteria are *vibrio* species and are predominant in seawater (Nagasawa and Cruz-Lacierda, 2004; Rivera, 2006). Many *Vibrio* species can cause disease in salmonids, but there are more reports of outbreaks by *Vibrio anguillarum* , *Vibrio salmonicida* (hitra disease; cold water vibriosis), *Moritella viscosa* (*Vibrio viscosus*) (Vintersår, winter ulcer), *Moritella logei*, and *Vibrio splendidus* (Noga, 2010).

Like motile *Aeromonas* sp., *Vibrio* can survive in aquatic environments, particularly in

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water above 17 °C (Pridgeon and Klesius, 2012). Depending on the strain, the optimal temperature is between 15 and 30°C. At temperatures above 20°C, cryophilic vibrios like *V. logei*, *V. wodanis*, and *V. salmonicida* grow poorly (Thompson *et al.,* 2004). All species are sensitive to acid and grow best at neutral or alkaline pH levels up to 9 (Igbinosa and Okoh, 2008).

Stressors due to chemical (diet, water quality, and pollution), physical (salinity and temperature), and biological (population density, macro- or microorganisms) agents/substances are all risk factors for vibriosis outbreaks in marine farmed fish including salmonids (Huicab-Pech *et al.,* 2016). Climate change, like other diseases, affects the epidemiological patterns of vibriosis as the changes in water temperature in early to mid-summer provide an optimal growth condition for *Vibrio* spp., as do low water quality, salinity fluctuations, and inadequate nutrition (Gratacap, 2008; Albert and Ransangan, 2013).

According to studies by the US Environmental Protection Agency, there is scientific evidence that global warming is increasing sea temperatures, including evidence that the aquatic temperature has risen by about 1 °C over the past 100 years (NOAA, 2021). However, there is a possibility that the polar ice caps will melt, which could lead to a decrease in seawater salinity worldwide. Given that vibrios, except for a few species, prefer warmer waters, the conditions are likely to facilitate the increase of the bacterial population with a consequent increase in the risk of vbriosis outbreaks (Roux *et al.,* 2015).

Rickettsiae

Piscirickettsia salmonis, the first pathogenic *Rickettsia* identified in fish, is a Gram-negative, immobile, aerobic, non-encapsulated, pleomorphic bacteria that is usually coccoid-shaped (Carrizo *et al.,* 2021). Piscirickettsia-like bacteria have been identified in freshwater and seawater fish species causing a significant impact on the aquaculture industry in different regions, including Chile, Scotland, Ireland, Norway, Croatia, Australia, New Zealand, and the Mediterranean Sea region (Cusack *et al.,* 2002; Mauel and Miller, 2002). The disease has been mostly reported in salmonids, but occasionally other species can also be infected (Zrnčić *et al.,* 2021).

The optimum temperature of *P. salmonis* is 15 to 18 °C, but it does not grow at 25 °C or more, which is the reason for its lack of growth in warm-blooded animals (Fryer *et al.,* 1990). Fluctuation in water temperature appears to be an important factor for disease outbreaks and the highest prevalence of the infection is observed in autumn and spring, which is probably due to the suitable temperature for bacterial multiplication in host tissues (Cvitanich *et al.,* 1990). Outside the host, the survival of *P. salmonis* is also affected by water temperature and salinity, as *P. salmonis* survives in seawater for a long time but is rapidly inactivated in freshwater. *P. salmonis* can tolerate seawater at 5 to 10 °C for 21 days, at 15 °C for 14 days, and at 20 °C for 7 days (Lannan and Fryer, 1994). Thus, the disease outbreak occurs after a period of extensive changes in the water

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environment, including temperature fluctuations and an increase in concentration of non-toxic algae (Branson and Diaz-munoz, 1991). With an increase in global climate change, such pathogens may adapt to the new conditions.

Climate change and disease outbreaks by Gram-positive bacteria

***Streptococcus* spp. and *Lactococcus* spp.**

Lactococcus garviae and *Streptococcus iniae* are two Gram-positive microorganisms that are more important bacterial species causing major health problems in many fish species of freshwater-, brackish-, and marine environments (Pękala-Safińska, 2018; A El-Noby *et al.,* 2021, Soltani *et al.,* 2021a; Van Doan *et al.,* 2022). Dependent on water temperature, streptococcal/lactococcal infections can be classified into warm-water infections caused by cocci species such as *L. garvieae, S. iniae, S. agalactiae, S. dysgalactiae*, *S. paraurberis*, and *S. uberis* and cold-water infections caused by cocci such as *Vagococcus salmoninarum* and *L. piscium* (Romalde *et al.,* 2008; Vendrell *et al.,* 2006). However, almost all streptococcal/lactococcal agents are able to invade aquatic organisms, including salmonids, in both cold and template aquatic ecosystems (Soltani *et al.,* 2005; Haghighi Karsidani *et al.,* 2010; Soltani *et al.,* 2014; Soltani *et al.*, 2021a, b; Van Doan *et al.,* 2022). Disease outbreaks in some regions, such as the Middle East, are highly serious problem in farmed trout, especially during the warm seasons (Soltani *et al.,* 2015). Therefore, a rise in inland water temperature caused by global warming is a significant predisposing factor in salmonid aquaculture (Soltani *et al.,* 2021b; Van Doan *et al.,* 2022).

Renibacterium salmoninarum

R. salmoninarum, as a Gram-positive bacterium, is the causative agent of bacterial kidney disease, one of the most serious bacterial infections in salmonid species (Delghandi *et al.,* 2020a; Fuentes *et al.,* 2022). It is a slow-growing organism with an optimal growth at temperature of 15 to 18°C, so with global warming, it could imply that a stress associated with rising water temperature contributes to the spread of disease in the northern and southern hemispheres (Delghandi *et al.,* 2020a). For instance, global warming can facilitate more disease outbreaks in farmed salmonids in regions such as North America, Europe, and Japan.

***Mycobacterium* spp.**

The bacteria are acid-fast, non-motile, aerobic bacilli belonging to the family *Mycobacteriaceae* of the order Actinomycetales, with an optimal growth temperature of 25-35 °C (Delghandi *et al.,* 2020b). Mycobacteriosis is a granulomatous disease that primarily affects aquarium fish and farmed food fish, particularly those raised in harsh conditions (Kumari *et al.,* 2020).

Fish mycobacteriosis is a chronic, progressive disease caused by nontuberculous mycobacteria, including *M. marinum*, *M. fortuitum*, and *M. chelonae* (Hashish *et al.,* 2018). Piscine mycobacteriosis is a common disease of marine, brackish, and freshwater fish that affects over 200 freshwater and marine fish species. Warmer temperatures can affect both

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the spread and the progression of fish mycobacteriosis worldwide (Collins *et al.,* 2020). Thus, fluctuations in water temperature are stressful to fish, making the host more vulnerable to the pathogens, as the ideal temperature for disease development is 25 °C-27 °C (Delghandi *et al.,* 2020b; Dar *et al.,* 2022).

Conclusion

Regarding the physiological features of bacterial fish pathogens, it is clearly understood that climate change, particularly global warming, can seriously affect the spread of disease in the aquaculture sector, including farmed salmonids. This is because global warming can reduce the generation time of the pathogenic mesophilic bacteria. However, the effects of climate change on the development of infectious diseases in aquaculture are complex and multifactorial and thus require more attention in detail.

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Conflict of interest

The authors have no conflict of interest in this work.

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