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Report of the Scientific Committee of the Spanish Agency for Food Safety and Nutrition (AESAN) on the effects of climate change on the risk of transmission of foodborne pathogens

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Working group

Antonio Valero Díaz (Coordinator), Rosa María Capita González, Baltasar Mayo Pérez, Azucena del Carmen Mora Gutiérrez, María Dolores Rodrigo Aliaga, Gloria Sánchez Moragas and Paula Arrabal Durán (AESAN)

Scientific Committee

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Technical Secretary
Vicente Calderón Pascual

Technical management of the report AESAN: Paula Arrabal Durán

Abstract

The Scientific Committee of the Spanish Agency for Food Safety and Nutrition (AESAN) has carried out an updated review of the scientific evidence on the influence of climate change on the transmission of foodborne pathogens. This global phenomenon represents an emerging threat to food safety and public health, since alterations in weather patterns such as increased temperatures, variability in rainfall and changes in environmental humidity directly affect the ecology, distribution and persistence of pathogens.

Various studies have shown that microorganisms such as *Salmonella* spp., *Campylobacter* spp.,

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Escherichia coli and species of the genus *Vibrio* are more prevalent in conditions of high temperatures. Likewise, humid and unstable environments favour enteric viruses and certain parasites. These conditions may also contribute to increased antimicrobial resistance. The globalization of agri-food systems has intensified the impact of climate change, expanding transmission routes and facilitating the introduction of pathogens into new regions through international trade. This scenario not only affects food safety in the short term, but also poses structural risks for the resilience and sustainability of food systems in the medium and long term.

Faced with this situation, it is a priority to reinforce epidemiological surveillance systems through the use of emerging technologies, including digital platforms for risk management. It is also essential to promote interdisciplinary research on the interactions between the climate and pathogens, promote international cooperation in the formulation of effective mitigation policies, and enhance public education and awareness of food risks linked to climate change. Preparing for extreme events, improving health infrastructures and investing in technologies for the detection, control and elimination of pathogenic microorganisms in food, water and contact surfaces are also key elements of a comprehensive prevention strategy.

Key words

Climate change, foodborne pathogens, food safety, globalization.

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1. Introduction

Climate change is an unequivocal reality, reflected in the increase in temperatures, the decrease in rainfall, extreme climatic events and the expansion of the semi-arid climate and exotic invasive species. Its effects on flora and fauna can compromise food safety and, as a result, the health of consumers (MITECO, 2020). Climate change is impacting the global food system through different direct and indirect pathways, posing new challenges for food security and human health (NIH, 2022).

The Intergovernmental Panel on Climate Change (IPCC) notes that climate change can affect food safety by modifying the population dynamics of polluting organisms, as a result of temperature changes and precipitation and humidity patterns, as well as by the increase in the frequency and intensity of extreme weather events (IPCC, 2022a). These factors can influence geographical and seasonal food distribution, as well as the survival of pathogens that cause foodborne diseases (Ziska et al., 2016) (NIH, 2022).

Some examples of how climate influences the biology of polluting organisms include changes in the activity of mycotoxin-producing fungi, changes in the presence of microorganisms in aquatic food chains (such as dinoflagellates, or bacteria of the genus *Vibrio*), and the increase in intense rains and floods that favour the contamination of pastures with enteric microorganisms such as *Salmonella*, facilitating their entry into the human food chain. In terrestrial environments, many foodborne pathogens come from enteric contamination of human or animal origin, and can be dispersed by wind (for example, through contaminated dust or soil) or by floods, both phenomena that are intensified by climate change (IPCC, 2019).

At the Conference of the Parties on Climate Change held in Baku in November 2024 (COP29), the impact of climate change on agri-food systems was addressed, which is linked to the change in rainfall patterns, unpredictable temperatures and a greater incidence of extreme weather events, with these effects favouring the spread of infection-causing microorganisms (COP29, 2024). Increased temperatures, in particular, could lead to a higher prevalence of microbial infections and, consequently, to the increase in antimicrobial resistance worldwide (Duchenne-Moutien and Neetoo, 2021). In fact, the Food and Agriculture Organization of the United Nations (FAO) has documented this phenomenon in several countries (FAO, 2020).

All this reinforces the need to implement measures to mitigate the impact of climate change on health. As an example, the Spanish Agency for Food Safety and Nutrition (AESAN) participates in the 2021-2025 Work Programme of the National Plan for Adaptation to Climate Change (MITECO, 2020), acting as the entity responsible for developing communication on food, health and sustainability, from a climate change perspective.

In this context, the AESAN Scientific Committee has been asked to review the scientific evidence currently available on the effects of climate change on the transmission of foodborne pathogens.

2. Climate change as a trigger for new food risks

Both climate variability and climate change pose significant threats to the safety of the food supply chain through various pathways. One of them is the possible worsening of foodborne diseases, affecting aspects such as the occurrence, persistence, virulence and, in some cases, the generation of toxins by pathogenic microorganisms. In addition, in relation to climate change, food safety can be compromised by chemical hazards, such as pesticides, mycotoxins and heavy metals.

Changes in weather patterns, such as decreased rainfall, increased rising air temperature and more frequent extreme weather events, have both direct and indirect impacts on public health. These include the scarcity of safe water for irrigation, the intensified use of pesticides due to pest resistance, difficulties in maintaining an adequate cold chain (which affects the safe preservation of food), and floods that carry chemical contaminants into water sources. Together, these factors can increase foodborne infectious diseases, food poisonings, antimicrobial resistance, and the bio-accumulation of chemicals and heavy metals in the human body (Duchenne-Moutien and Neetoo, 2021).

Climate change directly affects the abundance, growth, distribution and survival of pathogens, which modifies the prevalence of foodborne diseases (Peng et al., 2023). Pathogens can expand their geographical distribution, increasing the spread of diseases to new areas (Smith and Fazil, 2019). Among the critical factors, drinking water safety stands out as a key factor in the transmission of re-emerging infectious diseases. For example, increased rainfall and flooding can contaminate water supplies, raising the risk of outbreaks of waterborne diseases, such as those caused by *Salmonella*, *Cryptosporidium*, and enteric viruses (Lynch and Shaman, 2023).

Global warming, ocean acidification, droughts, forest fires, irregular rainfall and other extreme events are damaging food systems in unprecedented ways. Even one single environmental factor, such as the increase in temperature, can amplify multiple dangers to food safety, with repercussions on public health and international trade. Climate change affects the presence of microorganisms and pests, as well as the formation of toxins, which can lead to an increase in the incidence and intensity of food diseases. In addition, conditions such as the warming of marine surface waters and the increase in nutrients favour the proliferation of toxic algae, causing outbreaks of contamination in seafood (EFSA, 2020) (FAO, 2020). Therefore, climate change is also related to changes in the growth rates of pathogenic marine bacteria and other bacteria derived from faecal contamination, associated with the increase in water temperature (FAO, 2018). For example, the European Environment Agency (EEA) has reported an increase in *Vibrio* spp. infections in the Baltic Sea and predicts that this risk will continue to spread to the north (Vezzulli et al., 2016) (EFSA, 2024). In addition, a warmer climate can facilitate mutation and genetic transfer between microorganisms, promoting the appearance of pathogenic variants (FAO, 2018).

Extreme weather events, such as heat waves, storms, heavy rains and droughts are now more frequent and intense (IPCC, 2021). These phenomena generate multiple risks related to the presence and proliferation of pathogens, associated, among other factors, with:

- Favourable conditions for the proliferation of pathogens when affecting water treatment systems.
- Increased susceptibility of animals to diseases, increasing the excretion of pathogens.
- Alterations in the temporal patterns of infectious diseases.
- Development of bacterial resistance due to the intensive use of antimicrobials for veterinary use. Climate change favours bacterial resistance by altering temperatures and ecosystems, which increases stress in animals and encourages the use of antimicrobials.

- Introduction of pathogen vectors into new agricultural areas.
- Transport of infectious agents to farmland through flooding.

International initiatives have been developed such as the CLEFSA project (2018-2020) led by the European Food Safety Authority (EFSA) in Europe have been developed to address these challenges. This project established a multi-criteria methodology to assess emerging risks related to climate change. Among the risks identified, are the increase in the frequency and virulence of certain marine pathogens and toxins (EFSA, 2020).

Of particular concern are pathogens with low infectious doses, such as enteric viruses and *Campylobacter* spp., those with high environmental persistence, such as the *Mycobacterium avium* complex, and those that tolerate extreme variations in temperature and pH, such as *Salmonella* and *Escherichia coli*. In addition, some pathogens, such as *Coxiella*, can be transported long distances by the wind, increasing their dispersion (EFSA, 2020).

In this context, it is essential to adapt surveillance and control systems to deal with changes in the transmission of pathogen-related diseases in a climate-change scenario. Several recent studies confirm that the impact of climate change will increase foodborne toxi-infections, as well as other infectious diseases (Dietrich et al., 2023) (Awad et al., 2024) (Liao et al., 2024). At the national level, a recent report by the Scientific Advisory Committee on Food Safety of the Catalan Food Safety Agency (ACSA) evaluated the relationship between climate change and microbiological food safety (ACSA, 2025).

Below, the main pathogens associated with climate change and their repercussions on food security are described.

2.1 *Vibrio* spp.

Approximately 8 % of the world's population depends on seafood as a source of food and income. The main effects of climate change associated with the contamination of seafood are the increase in temperature in the upper layer of the ocean and its acidification, as well as a greater frequency of marine heat waves (Marques et al., 2010) (Kniel and Spanninger, 2017). *Vibrio* species are the main pathogenic organisms associated with seafood, and their appearance, frequency and severity are significantly affected by the temperature increase (Marques et al., 2010). These bacteria can cause serious infections, especially through the consumption of raw or under-cooked seafood, as well as infections of non-food origin (EFSA, 2024).

Numerous investigations document the association between the appearance of cholera and climate anomalies of the El Niño-Southern Oscillation (ENSO) type, which have a significant impact on extreme weather patterns in different parts of the world (Pascual et al., 2000) (Anyamba et al., 2019). Climate change is expected to increase the frequency and severity of ENSO events, based on observations collected in studies from East Africa, Peru and Bangladesh (Martinez-Urtaza et al., 2010) (Cai et al., 2014) (Cash et al., 2014) (Moore et al., 2017).

Specifically, ocean warming and intense rainfall, which reduce the salinity of coastal waters, seem to create favourable conditions for the proliferation of *V. vulnificus* and *V. cholerae*, which could explain the causes of outbreaks of vibriosis and cholera in areas where these diseases are uncommon (Vezzulli et al., 2013) (Burge et al., 2014) (Guzmán et al., 2015). Warmer water temperatures are also associated with the appearance of outbreaks of *V. parahaemolyticus* in Alaska (United States) (McLaughlin et al., 2005) (Martinez-Urtaza et al., 2010).

Historically associated with tropical regions, *V. parahaemolyticus* has been identified as the cause of outbreaks in temperate areas such as Galicia, in which pathogenic strains related to genetically diverse isolates from remote sources have been identified. A global-scale phylogenetic analysis revealed that most of clinical strains were unrelated, suggesting multiple episodic introductions from distant regions. The study also identified two key changes in the epidemiological dynamics: the initial appearance of cases and a transition in the pattern of outbreaks between 2015 and 2016, both associated with increases in the surface temperature of Galician coastal waters (Martínez-Urtaza et al., 2018).

Other emerging factors that affect *Vibrio*-associated infections include drought conditions, dust emissions, and wind direction (FAO, 2020). It is known that arthropods (adult flies, chironomids) can act as aerial vectors of *V. cholerae* and, with the wind, this bacterial infection spreads through the propagation of the vector, as reported in three cholera outbreaks in Africa and in the Indian subcontinent (Broza et al., 2005) (Paz and Broza, 2007) (FAO, 2020).

On the other hand, certain zooplanktons, such as copepods, act as marine reservoirs of *V. cholerae* (Vezzulli et al., 2010) (Lutz et al., 2013). It has been determined that climate change will likely alter the distribution of zooplankton populations in the global oceans, which could change the prevalence of *Vibrio* infections in the world (Brun et al., 2019). In addition, rainfall increases related to ENSO events are expected to increase the level of nutrients that enter river and coastal ecosystems, triggering greater plankton growth, which could promote an increase in *Vibrio* populations (Turner et al., 2014) (Greenfield et al., 2017). *V. cholerae* has been shown to proliferate together with the dinoflagellate *Lingulodinium polyedra* ("red tide"), which produces yessotoxins (Mouriño-Pérez et al., 2003). In Hong Kong SAR (China), cases of ciguatera poisoning preceded *V. cholerae* infections, according to a study that examined occurrence data between 1989 and 2001 (Kwan et al., 2003).

V. parahaemolyticus, *V. vulnificus* and *V. cholerae* non-O1/non-O139 are the *Vibrio* species of greatest significance for public health in the European Union through the consumption of seafood. The *V. parahaemolyticus* infection is associated with TDH and TRH hemolysins, and mainly causes acute gastroenteritis. *V. vulnificus* infections can lead to sepsis and be fatal in susceptible individuals. Non-O1/non-O139 *V. cholerae* can cause anything from mild gastroenteritis to serious infections, including sepsis, in vulnerable people. The joint estimate of the prevalence in seafood is 19.6 % for *V. parahaemolyticus*, 6.1 % for *V. vulnificus*, and 4.1 % for non-colerigenic *V. cholerae*. Approximately one in five positive products for *V. parahaemolyticus* contains pathogenic strains (EFSA, 2024). A wide spectrum of antimicrobial resistance has been detected in *Vibrio* isolated from seafood or foodborne infections in Europe, some of which are intrinsic. Moreover, antimicrobial resistance genes of medical importance associated with mobile genetic elements are increasingly being identified. While there are measures such as high-pressure processing, irradiation or purification which can reduce *Vibrio* levels in seafood, maintaining the cold chain is key to preventing its proliferation. According to the latest EFSA assessment (2024), the prevalence of *Vibrio* in seafood is expected to increase both globally and in Europe due to climate change, especially in low-salinity or brackish waters. It is estimated that as current warming trends continue, both infection rates and the burden of these diseases will increase, including infections in vulnerable populations lacking immunity. These findings underline the need for continuous surveillance and the implementation of new early warning and prediction strategies based on machine learning that are already being tested to predict complex environmental factors (Campbell et al., 2025).

2.2 *Aeromonas* spp.

They are ubiquitous bacteria in all aquatic ecosystems. They can be isolated from rivers, lakes, ponds, seawater, drinking water, groundwater, wastewater and wastewater in various phases of treatment (Janda and Abbott, 2010). *Aeromonas* spp. are also found in the soil and in plants (Lamy et al., 2022), and have been detected in chironomid insects (Laviad and Halpern, 2016), and in the intestinal tract of crustaceans (Zhao et al., 2018), fish (Ofek et al., 2021), birds (Laviad-Shitrit et al., 2018) and mammals (Lamy et al., 2022). They show remarkable adaptability to constantly changing environmental factors, and climate change seems to directly influence their virulence and pathogenicity.

Originally, *Aeromonas* spp. were associated with infections in fish and other cold-blooded animals, but this bacterium also affects immuno-compromised animals and human hosts, causing wound infections, cellulitis, sepsis and urinary tract infections (Schwartz et al., 2024). Many infections have been associated with previous contact with water during bathing or fishing or contact with food of animal origin (Spadaro et al., 2014) (Couturier et al., 2017) (Ganiatsa et al., 2020). Cases of Hemolytic Uremic Syndrome (HUS) associated with *Aeromonas*, in which food transmission was assumed, have also been reported (Figueras et al., 2007) (Castellano-Martinez et al., 2019).

At present, 36 species of *Aeromonas* are described. *A. hydrophila*, *A. dhakensis*, *A. veronii*, *A. salmonicida* and *A. caviae* cause significant economic losses in the aquaculture industry worldwide (Pang, 2023). The most frequently isolated strains from human clinical samples belong to the species *A. hydrophila*, *A. caviae* and *A. veronii* biovar *sobria* (Ruiz de Alegría-Puig et al., 2021) (Pessoa et al., 2022).

Rising temperatures and changing environmental conditions affect their growth, biofilm formation, and antimicrobial resistance. Thus, rising temperatures enhance biofilm production, which in turn can increase the virulence of these pathogens by improving their ability to withstand environmental stress. In addition, some strains show altered patterns of antimicrobial resistance with changes in temperature and pH, suggesting that climate-induced environmental changes could promote more *Aeromonas* spp. infections that are difficult to treat (Grilo et al., 2021).

A 2-year study carried out in Bangladesh, which investigated the presence of *Aeromonas* spp. in freshwater ponds, revealed that the amount of bacteria increases at two specific times of the year, before and after the monsoon season, and that this increase is directly related to the water temperature (Sadique et al., 2021). Regarding species diversity, *A. veronii* biovar *sobria* was the predominant species, representing 27 % of the 200 isolates characterized. Other species identified included *A. schubertii* (20 %), *A. hydrophila* (17 %), and *A. caviae* (13 %). The conclusions of the study highlight that the presence of *Aeromonas* species with multi-factorial virulence potential in domestic ponds, which are often used as sources of drinking water in the coastal region of Bangladesh, represents a significant potential risk to public health, especially in the context of increased global warming.

Other recent studies have shown that increased water temperature, low levels of dissolved oxygen and variations in pH impact the growth rate of *Aeromonas* spp. and the expression of virulence genes, which increases the risk of infections in both fish and humans. This mechanism is particularly relevant in *A. hydrophila*, which is responsible for numerous outbreaks in aquaculture and has zoonotic potential (Abdella et al., 2024) (Judan et al., 2024). As a projection for future studies, the development of mitigation strategies in aquaculture is suggested, through the regulation of environmental factors and the implementation of sustainable management practices in this industry, in order to reduce the risks posed by *Aeromonas* spp. in a climate change scenario.

2.3 *Salmonella* spp.

It is a highly persistent zoonotic enteric microorganism in poultry, as well as the main cause of acute gastroenteritis worldwide (Jiang et al., 2015). According to Herrera et al. (2016), previous research has documented that *Salmonella* infections are directly proportional to temperature. Currently, in Europe, most cases of salmonellosis are reported during the summer months and, in addition, the incidence of *Salmonella* is lower in the colder countries of the north compared to those with warmer climates (Dietrich et al., 2023). In several countries (Ireland, Australia, New Zealand and the United States, among others) it has been found that, for temperatures above 5 ºC, salmonellosis increases between 5 and 10 % for each 1 ºC increase in weekly temperature (Tirado et al., 2010) (Zhang et al., 2010) (Wu et al., 2016) (Khan et al., 2021). In this regard, it is estimated that warming related to climate change will favour the colonisation and growth of *Salmonella* in broiler chickens (Jiang et al., 2015), which, in the absence of adequate monitoring and good hygiene and handling practices, may lead to an increase in the transmission of the enterobacterium throughout the food chain. However, methodological issues, such as the high correlation between climatic variables (ambient temperature, rainfall and relative humidity), make it difficult to identify real explanatory factors and predict risk.

2.4 *Campylobacter* spp.

This is a ubiquitous pathogen in certain farm animals and is positioned as the etiological agent of the most frequently reported zoonoses in Europe during 2023 (EFSA/ECDC, 2024). A literature review study carried out by Austhof et al. (2024), concluded that temperature, increased flooding and fluctuations between periods of rain and drought are associated with an increase in *Campylobacter* infections in humans. Likewise, the proximity between agricultural activities and livestock operations significantly increases the risk of *Campylobacter* infections. One of the reasons is that warmer winters can favour the survival of various *Campylobacter* vectors, such as flies, which is expected to result in a significant increase in cases of campylobacteriosis (FAO, 2020). In general, in the context of climate change and climate variability, it is estimated that the incidence of campylobacteriosis, including vector-borne forms, will increase by about 3 % in the coming decades (Duchenne-Moutien and Neetoo, 2021). In this regard, it has already been quantified that, between 1999 and 2010 in Israel, an increase of 1 ºC above the temperature threshold of 27 ºC resulted in a 16.1 % increase in *C. jejuni* and 18.8 % in *C. coli* infections in all age groups (FAO, 2020).

2.5 Pathogenic *Escherichia coli*

Escherichia coli is a ubiquitous enterobacterium that is part, as a predominant species, of the normal aerobic and facultative anaerobic microbiota of the digestive tract in most mammals and birds. While most strains of *E. coli* are non-pathogenic members of the gut microbiota, where it plays a harmless or even beneficial role for the host, some strains are pathogenic due to the acquisition of specific virulence factors that give them the ability to produce a wide variety of infections in humans and animals, both enteric (diarrhoea, dysentery, haemorrhagic colitis, Hemolytic Uremic Syndrome and oedema disease) and extra-intestinal (urinary tract infections, bacteraemia or septicemia, meningitis, peritonitis, mastitis, and respiratory and wound infections). Based on the mechanisms of pathogenesis and virulence factors possessed by diarrheogenic *E. coli*, they have been included in six groups or categories: enteropathogenic *E. coli* (EPEC); enterotoxigenic *E. coli* (ETEC); enteroinvasive *E. coli* (EIEC); enterohaemorrhagic, verotoxigenic or Shiga toxin-producing *E. coli* (EHEC/VTEC/ STEC); enteroaggregative *E. coli* (EAEC); and diffuse adherence *E. coli* (DAEC). The group of EHEC/VTEC/STEC is a group of strains of *E. coli* capable of producing toxins very similar to the toxin produced by *Shigella dysenteriae* type 1 (AESAN, 2012). Specifically, Shiga toxin-producing *E. coli* (STEC) was the third most frequently reported zoonotic agent in humans in 2023 (10 217 confirmed human cases of infections with 3285 hospitalisations), after *Campylobacter* spp. and *Salmonella* spp. (EFSA, 2024).

The proliferation of *E. coli* in the environment is also affected by increased temperatures, which increases the risk of transmission, contamination and infection through the food chain (Balta et al., 2024). For example, EHEC O157 (enterohemorrhagic *E. coli*), known to cause severe outbreaks frequently linked to the consumption of under-cooked meat and raw vegetables, can proliferate in warmer conditions, which amplifies its transmission during heat waves. In a study performed in the United Kingdom between 2015 and 2019, Gilligham et al. (2023) observed that confirmed cases of Shiga toxin-producing *E. coli* (STEC) strains increased during the months of April and May, peaking between June and September. In England, during the same period, STEC cases increased from April to July (in 2016) or August (in the other years), and then decreased (WHO, 2019). Similar studies conclude that there is a relationship between the increase in temperature and the concentration of *E. coli* in oysters (Billah and Rahman, 2022), in unpasteurised cow's milk (Feliciano et al., 2021) and in leafy vegetables (Duchenne-Moutien and Neetoo, 2021).

On the other hand, heavy rains and floods can affect wastewater treatment facilities, making it difficult to process and resulting in inefficient treatment. This is particularly concerning, as enterotoxigenic *E. coli* (ETEC) strains are primarily transmitted through contaminated water and is one of the leading causes of traveller's diarrhoea in developing regions with poor sanitation. For example, in a study carried out by Aijuka and Buys (2019) in Bangladesh, the formation of ETEC biofilms on surfaces in contact with drinking water correlated with hot and humid months, and with the increase in diarrhoeal diseases.

The phenomena associated with climate change can influence the incidence of the different pathotypes of *E. coli* in agricultural practices. The increase in temperature and modifications in rainfall affect their persistence and distribution in the crops, highlighting the risk of the presence of enteroaggregative *E. coli* (EAEC) and *E. coli* with diffuse adherence (DAEC), due to their ability to adhere to plants. In addition, the use of untreated wastewater for irrigation, driven by water scarcity, can introduce pathogenic *E. coli* into the food chain, generating health concerns. Likewise, enteropathogenic strains such as enteropathogenic *E. coli* (EPEC) and enteroinvasive *E. coli* (EIEC), associated with person-to-person transmission and food outbreaks, could have their transmission dynamics altered due to changes in human behaviour and hygiene practices during extreme weather events (Balta et al., 2024).

2.6 Mycotoxin-producing fungi

Mycotoxins are secondary metabolites produced by filamentous fungi that belong mainly to the genera *Aspergillus*, *Fusarium*, *Penicillium* and *Alternaria*. The most toxic mycotoxins include aflatoxins, zearalenone, trichothecenes, fumonisins and ochratoxins, since they possess carcinogenic and immuno-suppressive properties, affecting both humans and animals (Ostry et al., 2017) (Agriopoulou et al., 2020) (AESAN, 2021).

Mycotoxigenic fungi can colonize various staple crops, such as corn, rice, wheat, as well as nuts, coffee, grains, dried fruits, spices, fodder crops, fruits and vegetables, where they can in turn produce mycotoxins that affect food safety. For example, there is growing concern about fungal diseases caused by *Fusarium* and *Aspergillus* spp. in basic crops, since they not only cause yield losses, but are also producers of mycotoxins that enter the food chain (Balendres et al., 2019) (Agriopoulou et al., 2020).

It is believed that mycotoxin contamination of food is aggravated by the effects of climate change (FAO, 2020) (Duchenne-Moutien and Neetoo, 2021). The principal climatic factors involved in the occurrence and prevalence of mycotoxigenic fungi are temperature and humidity. In addition, it has been found that changes in rainfall patterns also increase the risk of mycotoxins in various ways (FAO, 2020). Drought conditions can weaken the natural defences of crops, making them more susceptible to fungal growth and toxin production, while heavy rains followed by high temperatures can generate moisture that favours fungal growth. Some secondary factors that affect mycotoxin contamination in crops include the displacement of existing fungal species by more virulent fungi, pest attacks, loss of efficacy of fungicides and pesticides, and changes in the geographical distribution of insects (FAO, 2020).

EFSA carried out a project to model, predict and map the possible increase in aflatoxin B1 contamination in cereals within the European Union due to climate change (Battilani et al., 2012). This project, completed in 2012, used climate change scenarios to assess the risk of *Aspergillus flavus* growth and consequent aflatoxin production in key cereal crops such as maize, wheat and rice. The findings indicated that warmer and wetter weather conditions predicted in central and northern Europe, could increase the likelihood of *A. flavus* proliferation in corn crops, posing a significant health risk due to the carcinogenic nature of aflatoxins. The study highlighted the direct impact of seasonal variations and the increase in global temperatures on aflatoxin levels in cereals. The EFSA report emphasized the need for continuous monitoring and the implementation of good agricultural and post-harvest practices to mitigate these emerging risks (Battilani et al., 2012).

Likewise, the AESAN Scientific Committee report on the effects of climate change on the presence of mycotoxins in food (AESAN, 2021) indicates that the scientific evidence points to a geographical redistribution of the incidence of the different mycotoxins, and that, focusing on southern Europe, a clear increase in the incidence of aflatoxins in corn, traditionally linked to tropical climates, can be expected, as well as an aggravation of the already existing problem of fumonisins in this same cereal. Likewise, the temperature and precipitation patterns projected for climate change in Europe suggest that areas such as central and northern Europe could lead to an increase in the presence of *A. flavus* and *A. parasiticus* due to a warmer and wetter climate, which increases the risk of contamination in staple foods, especially in corn and nuts. This represents a significant challenge for food safety, since aflatoxins are highly toxic and stable to heat treatment, making them difficult to eliminate during food processing (Medina et al., 2014).

More recent studies point in the same direction: the increase in temperatures and precipitation fluctuations can generate conditions that favour the contamination of crops by *A. flavus*. For example, in Illinois (United States), geospatial models show that both increased rainfall during the pre-planting period and higher temperatures during flowering and harvesting are associated with higher levels of aflatoxin and fumonisin contamination (Castano-Duque et al., 2023).

2.7 Enteric viruses

Climate change significantly influences the transmission of foodborne viral diseases by modifying environmental conditions that favour the persistence and spread of pathogens in the food chain. In particular, the increase in global temperatures could reduce the persistence of enteric viruses in the environment and in food; however, this same heating can promote bacterial growth in these matrices, which in turn facilitates the formation of biofilms that, indirectly, offer a protective environment for said viruses, partially counteracting the negative effect of heat on their survival (Samandoulgou et al., 2021) (Gagné et al., 2022). At the same time, the greater frequency of extreme weather events such as floods and droughts creates environments conducive to the contamination of crops and food with enteric viruses, such as noroviruses and the hepatitis A virus. In addition, the globalisation of food systems amplifies these risks, since contaminated food can be quickly distributed internationally.

Another worrying factor is the impact of water stress associated with climate change, which encourages the use of treated wastewater for irrigation (Girón-Guzmán et al., 2024). If treatment systems are not adequate, environmentally resistant viruses can survive and contaminate food. Taken together, these dynamics put food safety at risk and underline the need to strengthen health surveillance, implement stricter standards in water management and promote safe agricultural practices in the face of the challenges of climate change.

2.8 Parasites

Foodborne parasites, most of which are zoonotic agents, represent a major danger to public health. These foodborne pathogens, including protozoa (e.g., *Cryptosporidium* spp., *Cyclospora cayetanensis* or *Toxoplasma gondii*) and helminths (e.g. *Fasciola* spp., *Paragonimus* spp., *Echinococcus* spp., *Taenia* spp., *Angiostrongylus* spp., *Anisakis* spp., *Ascaris* spp., *Capillaria* spp., *Toxocara* spp., *Trichinella* spp. or *Trichostrongylus* spp.), have accompanied the human species since its origins. Persistent or extreme changes in temperature, the level of precipitation, humidity and air pollution associated with climate change have a direct influence on the life cycles of parasites transmitted through food, increasing or reducing the survival and infectivity of parasitic forms present in the environment. These factors can also affect the biology of hosts (for example, by increasing their distribution), increase contact between parasite and host or alter the health of susceptible populations, which could increase the prevalence of parasitic diseases (Froeschke et al., 2010) (Liao et al., 2024). Therefore, although less recognised than other consequences of climate change, the emergence and re-emergence of certain parasitic diseases is, at present, an important cause for concern (Short et al., 2017). It should be noted, however, that the effects of climate change on parasites transmitted through food are very complex. Table 1 shows the influence of climate change and globalisation on some foodborne parasites.

Table 1. Influence of globalisation and climate change on foodborne parasites

Parasites	Climate change		Globalisation	
	Factors that favour the increase in the prevalence of human infections	**Factors that favour the decrease in the prevalence of human infections**	**Factors that favour the increase in the prevalence of human infections**	**Factors that favour the decrease in the prevalence of human infections**
Cyclospora cayetanensis, *Cryptosporidium* spp., *Giardia duodenalis*	Reduction of the number of drinking water sources Increase in the use of untreated wastewater for vegetable irrigation	Reduction of oocyst survival in the environment as a result of higher temperatures and periods of drought	Increase in the number of travellers	-
Toxoplasma gondii	Reduction of the number of drinking water sources Increase in the use of untreated wastewater for vegetable irrigation	Reduction of oocyst survival in the environment as a result of higher temperatures and periods of drought	Introduction of atypical strains in non-endemic countries from endemic countries	Increased awareness of the hazard Increased consumption of industrially produced pigs
Ascaris spp., *Trichuris trichura*	Reduction of the number of drinking water sources Increase in the use of untreated wastewater for vegetable irrigation	Reduction in the use of manure of human origin as orchard fertilizer Increased use of latrines and toilets	-	Increased personal hygiene Increased appropriate treatment of human faeces
Trichinella spp.	Increasing wild boar population	Reduction of the survival time of the larvae in the corpses of the hosts Reduction in wildlife habitat	Illegal import of meat Introduction of new eating habits Introduction of new host species	Increased pig rearing under suitable containment systems
Echinococcus granulosus s.l.	Pasture runoff Increased use of wastewater Decreased use of drinking water	Reduction of the survival of eggs in the environment as a result of the increase in temperatures and duration of drought periods	Immigration of herders and flocks from endemic countries to non-endemic countries	Improved personal hygiene practices

Table 1. Influence of globalisation and climate change on foodborne parasites

Parasites	Climate change		Globalisation	
	Factors that favour the increase in the prevalence of human infections	**Factors that favour the decrease in the prevalence of human infections**	**Factors that favour the increase in the prevalence of human infections**	**Factors that favour the decrease in the prevalence of human infections**
Echinococcus multilocularis	An increase in rodent populations in urban and peri-urban areas Decrease in quality water sources	-	Introduction of infested dogs from endemic regions to non-endemic regions	Improved personal hygiene practices
Liver parasites	-	-	Import of infected fish Introduction of new eating habits	Increased consumption of freshwater fish from industrial farms Reduction in the consumption of wild freshwater fish
Fasciola spp.	Increase in flooded areas due to the increase in torrential rains	Reduction of the survival of the cercariae as a consequence of the increase in temperatures and duration of the periods of drought	Introduction of infected animals from endemic countries to non-endemic countries	Increased infection control
Taenia saginata	Increased use of poor quality water for cattle	-	Introduction of infected cattle from endemic countries to non-endemic countries Increase in people defecating in cattle pasture areas	Increased controls on cattle destined for the international market
Taenia solium	-	Reduction of the survival of eggs in the environment as a result of the increase in temperatures and duration of drought periods	Increased movement of people from endemic to non-endemic countries	Decreased pig production in domestic and outdoor pens Increased use of latrines and toilets inaccessible to pigs

Source: (Pozio, 2020).

Climate change leads to increased temperatures and changes in precipitation patterns which generally create an environment conducive to the growth and survival of foodborne parasites. For example, warmer temperatures can increase the metabolic rate of parasites, allowing them to reproduce faster and reach higher population levels (Dietrich et al., 2023). In addition, altered precipitation patterns can increase humidity, improving parasite survival and dispersal (Polley, 2015).

A clear and significant effect of climate change on parasitic diseases can be seen in the case of trematodes, in which temperature directly affects crucial stages of their life cycle. Thus, the formation and emergence of free-living infective forms (cercariae) in the first intermediate hosts (molluscs) have a strong positive correlation with temperature (Poulin, 2006). At the same time, the infectivity of cercariae in the second intermediate hosts (invertebrates or fish, depending on the species) is also positively correlated with temperature (Studer et al., 2013). Since the transmission of cercariae is a crucial stage in the life cycle of trematodes, it has been suggested that global warming could substantially increase host infection rates (Marcogliese, 2001) (Poulin, 2006). However, while an elevated temperature accelerates the development of parasites in the environment and in ectothermic hosts, it shortens the survival time of eggs, larvae and cysts/oocysts (Mignatti et al., 2016). An increase in temperature as a result of climate change can also favour the establishment of parasites from tropical areas in temperate regions, as is the case with *C. cayetanenis* (Semenza et al., 2012a).

High humidity promotes the survival of parasitic eggs, larvae and cysts/oocysts. Intense rains associated with climate change also contribute to the dissemination of eggs, oocysts and cysts through contaminated water (Jiménez et al., 2010). It has also been observed that periods of drought reduce the survival of parasitic eggs, larvae, cysts and oocysts in the environment (Mignatti et al., 2016), but increase their concentration in the water, so that in the absence of quality water resources, the risk of outbreaks due to the consumption of contaminated water increases.

In this context, climate change can put pressure on farms, which try to maintain their productivity during periods of drought and intense rainfall at the cost of increasing the use of fertilizers (Lal, 2004). Fertilizers of animal origin may contain some parasitic forms. On the other hand, heavy rainfall events, which can increase in frequency and intensity due to climate change, drag fertilizers into local waterways (Joseph et al., 1991). Intense rains can extract cysts and oocysts from the soil and grass (Smith et al., 1989) and these events have been associated, for example, with outbreaks of cryptosporidiosis and giardiasis (Hunter, 2003).

Once these parasites are in a waterway, two scenarios can occur. First, extreme rainfall and flooding make some wastewater treatment plants unable to adapt to the large volume of effluent they receive. Wastewater treatment plants are usually equipped with overflow systems that cause excess wastewater not to be subjected to purification treatment, except for the passage through a primary filter that eliminates large waste. This sewage with infective microorganisms (including parasites) returns to the waterway untreated. This problem is aggravated in the case of island regions, which are easily flooded during extreme weather events, such as hurricanes, even contaminating groundwater (Detay et al., 1989). For example, in 1987, a sudden increase in cases of amebiasis was observed in the Chuuk Islands, in the Federated States of Micronesia, as a result of Typhoon Nina (Short et al., 2017).

Secondly, parasites present in waterways can resist the disinfection treatments used during water purification. For example, *Cryptosporidium* spp. oocysts are resistant to chlorinated compounds (Korich et al., 1990). Other disinfection methods, such as ultraviolet light (UVA), are not always effective in disabling these oocysts. Water temperature and time of exposure to UVA light influence the effectiveness of these treatments (Morita et al., 2002). In any of the indicated cases, people can come into contact with contaminated water and ingest the parasites.

Specifically with regard to helminths, these parasites interact directly with the environment when a part of their life takes place outside the hosts. Some nematodes, such as *Ascaris lumbricoides* and *Trichuris trichura*, are present in the soil before infecting the host, and certain components of the soil may be altered as a result of climate change (Weaver et al., 2010). High temperatures can accelerate the development of the larvae (Kim et al., 2012). An increase in rainfall can prevent the desiccation of eggs and larvae, thus allowing greater survival rates (Weaver et al., 2010). On the other hand, regions with low rainfall often have few resources to maintain personal hygiene, which can increase the prevalence of *A. lumbricoides* and *T. trichuria* infections. In this sense, an increasing incidence of human infections by *Fasciola* spp. has been observed as a consequence of the increase in torrential rains (Pozio, 2020).

Climate change also affects the distribution and behaviour of host animals. For example, changes in temperature and rainfall patterns can cause changes in the geographical distribution of hosts, leading to the expansion of parasite populations to new areas (Utaaker and Robertson, 2015). In addition, changes in host behaviour, such as alterations in migration patterns, can increase the likelihood of parasite transmission (Lafferty, 2009). Ultimately, the increase in the prevalence and distribution of parasites can increase food contamination, which poses a danger to human health (Short et al., 2017) (Pandey et al., 2023).

On the other hand, heating and high temperatures can cause the inactivation of some forms of parasite dispersion. Elevated temperatures and periods of prolonged drought reduce the survival in the environment of *Echinococcus granulosus*, *Echinococcus multilocularis*, *Taenia saginata*, *Taenia solium*, a fact that has also been observed in the case of the cercariae of *Fasciola* spp. and the oocysts of *Cyclospora cayetanensis*, *Cryptosporidium* spp. and *Giardia duodenalis*, resulting in a decrease in the prevalence of human infections by parasites transmitted through food (Pozio, 2020).

Moreover, recent studies indicate that some environmental factors may reduce the risk of disease for host animals, for example, through predation of parasite-free life forms. This refers to the elimination of the stages of the parasite that exist outside the host (for example, eggs, larvae or infectious forms present in water, soil or food) by natural predators such as protozoa, copepods, aquatic insects or other microorganisms. This ecological interaction can reduce the parasitic load on the environment, thereby decreasing the risk of infection for human or animal hosts. Parasite-host dynamics are not influenced by abiotic conditions, such as temperature, but by interactions with other species in the environment. For example, some organisms of the ecological community of which a parasite-host system is a part can cause a reduction in the risk of certain diseases through a phenomenon called the "dilution effect". This effect is mainly related to variable host compatibility, where the presence of low compatibility hosts leads to a reduction in the risk of disease for competent hosts (Keesing et al., 2006). However, the initial concept has recently been expanded to include the effects of species that do not serve as hosts (Johnson and Thieltges, 2010) (Johnson et al., 2010). When these non-host animals consume the infectious forms of free life parasites, they can interfere with their transmission (Keesing et al., 2006) and cause reduced levels of infection in the target host (Johnson and Thieltges, 2010). Experimental and observational studies, both laboratory and field, indicate that such predation effects affect different parasites with free life stages (Thieltges et al., 2009) (Orlofské et al., 2012) (Welsh et al., 2014), suggesting them as important regulatory mechanisms for many parasitic diseases (Keesing et al., 2010) (Ostfeld and Keesing, 2012).

Based on the generally positive correlation between the metabolic rates of ectothermic organisms and ambient temperature (Schmidt-Nielsen, 1997), the intensity of predation of parasitic forms by these animals is temperature-mediated. The rise in metabolism leads to higher feeding rates, which increase up to an optimum temperature, beyond which they decline due to thermal stress (Englund et al., 2011). Therefore, what is indicated suggests a potential interaction between the effect of temperature and the effect of predation. Thus, the increase in parasitic populations and infectivity at high temperatures could be compensated by the increase in the feeding rate of some predators of free-living parasitic forms, which suggests that the effect of climate change on parasitic diseases could be scarce and even non-existent (Goedknegt et al., 2015).

2.9 Dinoflagellates, diatoms and cyanobacteria

Marine phytoplankton are a diverse group of primary producing microorganisms, which contribute approximately 50 % of the global carbon fixation and form the basis of the biological pump that transports carbon from the atmosphere to the depths of the ocean (Siegel et al., 2023). As the main functional groups of the phytoplankton community, dinoflagellates and diatoms support most marine food networks and play key roles in ecosystems and bio-geochemistry (Collins et al., 2014). On the other hand, some species of dinoflagellates and diatoms are pathogenic, representing approximately 75 % and 5 %, respectively, of all phytoplankton species that cause Harmful Algae Blooms (HAB), phenomena that can adversely affect public health, as well as fisheries and aquaculture (Xiao et al., 2018).

HAB consist of the rapid spread of natural microalgae or macroalgae to high levels that damage the environment. It is known that several marine microalgae responsible for HAB produce natural toxins, known as phycotoxins (Pulido, 2016). Consumption of aquatic animals caught in waters with HAB creates a pathway for these toxins to enter the food chain. Prokaryotic microalgae, such as cyanobacteria, produce cyanotoxins, while dinoflagellates and diatoms, which are eukaryotes, produce marine biotoxins, also known as seaweed toxins. Several phycotoxins are neurotoxic and threaten human health and food safety (Pulido, 2016). For example, cyanotoxins can contaminate freshwater deposits and drinking water, thus posing a direct threat to human health (Cheung et al., 2013). As for marine biotoxins, they accumulate organically in various tissues of aquatic organisms, such as bivalve molluscs and fish, and enter the food chain after consumption. For example, the intake of seafood contaminated by saxitoxins produced by microorganisms of the genus *Alexandrium* can cause paralysing seafood poisoning (Fox, 2012).

Climate change is transforming aquatic ecosystems. Coastal waters have experienced progressive warming, acidification and deoxygenation, aspects that will intensify throughout the 21st century. The frequency of HAB has increased in recent decades and it is foreseeable that this trend will continue in the future (Wells et al., 2015), although the degree to which climate change is causing this increase in blooms is not fully clarified, since there are other factors that influence the appearance of HAB (for example, tourism and aquaculture) (Gobler, 2020).

The specific climatic factors involved in the prevalence of these blooms are, mainly, temperature, stratification, light, ocean acidification, precipitation and wind (Wells et al., 2015). In this context, it is logical to think that, under a changing climate scenario, the current spatial and temporal distribution of the species responsible for blooms will be altered. Spatially, the geographical areas where these species are located can expand, decrease or change latitudinally. With regard to temporal distribution, rising atmospheric and water temperatures may alter seasonal patterns, likely prolonging summer conditions and influencing the occurrence of HAB (Wells et al., 2015).

It is well established that changes in hydrological conditions (for example, temperature or nutrient availability) can alter the relative abundance and distribution of dinoflagellates and diatoms (Hinder et al., 2012), as well as in the incidence of HAB (O'Neil et al., 2012) (Wells et al., 2015). Therefore, climate change and human activities (warming and eutrophication) are factors that can affect marine ecosystems and have a substantial impact on the dynamics of dinoflagellates and diatoms (Cheung et al., 2021). Eutrophication has caused substantial phytoplankton proliferation and the expansion of low-oxygen areas (Edwards et al., 2006). Warming affects phytoplankton in two different ways: directly through the effect of temperature on the metabolic rates of microorganisms and indirectly through physical mixing, which affects the availability of nutrients (Lewandowska et al., 2014). The relationship between climate change and marine blooms is exemplified by the increase in ciguatera poisonings observed in the tropical Pacific during the El Niño period (Marques et al., 2010).

Xiao et al. (2018) revealed that dinoflagellates and diatoms respond differently to temperature, nutrient concentrations and ratios, and their interactions. Diatoms prefer lower temperatures and higher nutrient concentrations, while dinoflagellates are less sensitive to temperature and nutrient concentrations, but tend to prevail with low phosphorus concentrations and a high nitrogen/phosphorus (N/P) ratio. These different characteristics of diatoms and dinoflagellates mean that both the effect of warming, which results in a decrease in nutrients as a consequence of the increase in stratification, and the effect of the increase in the supply of terrestrial nutrients (N) as a result of eutrophication, could favour the predominance of dinoflagellates over diatoms. In this sense, Xiao et al. (2018) predict that, with conservative climate change forecasts for the year 2100, there will probably be a 60 % decrease in diatoms and a 70 % increase in dinoflagellates in the surface waters of the East China Sea, which means that diatoms could decrease by 19 % and dinoflagellates increase by 60 % in the surface waters of the East China Sea coast. In other studies, however, an increase in diatoms and a decrease in dinoflagellates in the northeast Atlantic Ocean in recent years has been observed in the past decades (Hinder et al., 2012) (Cheung et al., 2021). One possible reason for these differences is that diatoms and dinoflagellates can exhibit plastic responses to environmental stress on different time scales, or that the effects of warming and eutrophication probably depend on other environmental factors in the different regions studied (Lewandowska et al., 2014) (Grimaud et al., 2017).

Although temperature plays an important role in the different stages of growth and flowering of phytoplankton, and these processes are expected to change in response to climate change, it is difficult to predict the meaning and size of these changes, which depend on different factors. Thus, it is expected that some coastal regions may be more affected by global warming than others. A requirement for the increase in temperatures to increase the frequency of blooms in a given place is that the temperature reached does not exceed those that support maximum growth. There are many cases in which this scenario has already occurred, with HAB being intensified as the waters approach the temperatures that produce the maximum growth of the microorganisms responsible for these blooms (Gobler et al., 2017). There are also places where this event is expected to occur in the future (Glibert et al., 2014). Cyanobacteria blooms in freshwater appear to be the most obvious example of warming-induced intensification with cases described in different geographical areas, indicating that the temperatures that produce the peak growth rates for many cyanobacteria responsible for the blooms are higher than those of non-harmful eukaryotic algae (Paerl and Huisman, 2008, 2009). In marine systems, warming has been implicated in the intensification of multiple HAB in several mid- and high-latitude regions (Moore et al., 2009) (Gobler et al., 2017) (Griffith et al., 2019). However, this increase in blooms may be balanced with what happens in other areas, where the number of HAB decreases when the temperature increases above the optimal range of growth of microorganisms (Griffith et al., 2019). On the whole, this leads to a scenario in which the HAB may be moving towards the poles as a result of global warming (Hallegraeff, 2010) (Gobler et al., 2017) (Griffith et al., 2019).

The migration of HAB to new geographical areas can create significant risks for aquatic ecosystems and the humans living near them. Species that had never been exposed to a certain HAB and/or its harmful effects may be the first to experience selective pressures and thus suffer large demographic decreases (Colin and Dam, 2002) (Bricelj et al., 2005). In addition, regulatory agencies and health systems that have not previously considered, monitored or treated HAB poisonings may respond inadequately when the first cases of contamination of aquatic products or human food poisonings from this cause occur.

Yet the fundamental cause of ocean warming is the accumulation of carbon dioxide (CO_2) in the atmosphere, which acidifies the ocean surface (Doney et al., 2009). In doing so, this greater availability of CO_2 offers the potential to rebalance the distribution and abundance of primary producers that depend on inorganic carbon to perform photosynthesis (Giordano et al., 2005). While the effect of increased CO_2 on phytoplankton communities is not fully explained, it has been hypothesized that, since the Rubisco enzyme found in dinoflagellates has less affinity for CO_2 than that of other phytoplankton organisms, dinoflagellates, which cause most marine HAB, are more likely to benefit from increased CO_2 levels than other classes of algae (Reinfelder, 2011). While this hypothesis oversimplifies the effects of high CO_2 emissions on phytoplankton populations, it has found support in a meta-analysis of 26 studied HAB that showed that the growth rates of harmful algae increased consistently with high CO_2 levels, while non-harmful algae do not show this trend (Brandenburg et al., 2019).

In addition to the decrease in pH, ocean acidification is causing a state of saturation of calcium carbonate in the ocean (Doney et al., 2009), which represents a threat to the growth and survival of aquatic organisms (Gobler and Baumann, 2016). Many harmful blooms, especially those of freshwater, occur during the maximum temperature peak in summer, and the high levels of biomass generated increase the amount of organic matter, which in turn promotes hypoxia and acidification (Wallace et al., 2014). In this regard, it should be noted that dissolved oxygen levels in the ocean have been decreasing since the mid-20th century and this trend is expected to continue during the 21st century, as warmer waters retain less dissolved oxygen (Breitburg et al., 2018).

One of the major complexities of climate change lies in the multitude of processes that are changing simultaneously. One of these processes is eutrophication, since changes in nutrient loads can intensify HAB. Although eutrophication is a phenomenon with a markedly anthropogenic character, some climate change processes, such as changed patterns of precipitation, can independently intensify nutrient load rates (Sinha et al., 2017) and, in turn, increase the frequency of HAB.

3. Effects of factors associated with climate change on the incidence of foodborne pathogens

As described in previous sections, the impact of climate change on food production systems has many influencing factors. It has also been recognized that climate change could have a potential effect on the increase in microbial contamination of food, waste and water, which in turn could generate a change in the risks associated with infectious diseases transmitted through water and food (Miraglia et al., 2009).

The possible impacts of climate change on the increase in foodborne toxi-infections are manifested by: i) the seasonal variability associated with temperature fluctuations (Lake et al., 2009); ii) the historical links between extreme weather events and the increase in the incidence of diseases transmitted through food and water (Hall et al., 2002); and iii) the fact that many diseases transmitted through food are seasonal in nature (Hall et al., 2002).

Therefore, knowledge of the influence of these factors can help develop risk mitigation strategies against the increase in the spread of emerging pathogens as a result of phenomena associated with climate change. These factors are summarised in Table 2.

Table 2. Main effects of climate-related environmental factors on the behaviour of foodborne pathogens

Ambient factors	Effect of climate change on environmental factors involved in the growth, survival and virulence of foodborne pathogens	References
Temperature		
Increase	Increased prevalence of parasites in freshwater fish and plants	Herrera et al. (2016)
	Detection of new species of mycotoxin-producing moulds in corn in Europe	Moretti et al. (2018)
	Increased incidence of mastitis in cattle	Lacetera (2019)
	Increased prevalence of *Salmonella* in poultry	Herrera et al. (2016)
	Increased *Vibrio* concentration in seafood	Marques et al. (2010)

Table 2. Main effects of climate-related environmental factors on the behaviour of foodborne pathogens		
Ambient factors	**Effect of climate change on environmental factors involved in the growth, survival and virulence of foodborne pathogens**	**References**
Decrease	Increased contamination of berries with hepatitis A virus	Calder et al. (2003) EFSA (2014)
Rainfall and humidity		
Increasing rainfall	Penetration of pathogenic strains of *Escherichia coli* and *Salmonella* in green leafy vegetables	Ge et al. (2012) Liu et al. (2013)
	Increased contamination of seafood with indicators of faecal contamination due to water runoff	Marques et al. (2010)
	Increased risk of dispersion of *Salmonella* by splashes and aerosols infecting tomatoes due to increased frequency of heavy rains for short periods	Cevallos-Cevallos et al. (2012)
Decrease in rainfall and humidity	Increased contamination with mycotoxins formed by xerophilic moulds in corn in the pre-harvest stage	Moretti et al. (2018)
pH and salinity		
Decrease in pH	Ocean acidification that causes an increase in Harmful Algae Blooms	Marques et al. (2010)
Light		
Increase	An increase in Harmful Algae Blooms	Marques et al. (2010)

Source: (Duchenne-Moutien and Neetoo, 2021).

3.1 Temperature

The constant increase in the planet's temperature is recognized as one of the most critical factors in the increase in the incidence of emerging foodborne pathogens. Risks to health, livelihoods, food safety, water supply, human security and economic growth due to climate change are expected to increase with 1.5 °C warming and further increase with 2 °C. According to this analysis, any increase in global temperature will have a negative impact on human health (IPCC, 2022a). The increase in temperature is closely linked to the rise in sea levels, which causes the melting of the polar ice caps and the possible thermal expansion of the oceans. Warming seawater and the effects of coastal erosion can alter ecosystems, influence biodiversity, and introduce new potential microbiological threats. Elevated temperatures associated with extreme weather events could increase both the prevalence of pathogens and their rate of multiplication, resulting in a higher level of contamination (Kendrovski and Gjorgjev, 2012). Therefore, it is essential to study the epidemiology of infectious diseases and analyse the potential impact of climate change on disease patterns, the survival of pathogens and their transmission (McMichael et al., 2006).

Many pathogens can proliferate rapidly in warm environments, with optimal growth temperatures ranging between 20 and 45 °C (Bintsis, 2017). As temperatures increase due to climate change, the range and distribution of foodborne pathogens is also expected to change (Smith and Fazil, 2019).

Therefore, temperature plays a crucial role in the spread of pathogens transmitted through food by creating ideal conditions for their growth and survival. Warmer temperatures also increase the metabolic activity of microorganisms, allowing them to grow and reproduce more quickly (Qiu et al., 2022). For example, *Salmonella*, enterohemorrhagic *E. coli* (EHEC) or *C. jejuni* are the most common food pathogens that proliferate in warm environments (Dietrich et al., 2023). These pathogens have low infective doses and can survive in unfavourable environmental conditions of temperature and pH (FAO, 2008). Foodborne infections caused by *Salmonella* have been frequently associated with increases in temperature. In this case, 30 % of the reported cases of salmonellosis have been attributed to warm temperatures.

Other studies show the correlation between the variables associated with the climatic conditions of temperature with the incidence of foodborne infections. Kim et al. (2015) studied the effect of seasonal temperature variations during the years 2003-2012, in South Korea, and observed that *E. coli*, *V. parahaemolyticus*, *C. jejuni*, *Salmonella* spp. and *Bacillus cereus* were the pathogens that showed the highest correlation with respect to temperature increase. In the case of *Campylobacter* spp., the results from the European Centre for Disease Prevention and Control corroborate this fact (ECDC, 2021). Also, Kuhn et al. (2020) estimated that the number of foodborne *Campylobacter* cases will double in four northern European countries (Denmark, Finland, Norway and Sweden) by the end of the 2080s, with an additional 6000 cases per year due to climate change.

In addition, changes in temperature and precipitation patterns can alter the geographical distribution of mycotoxin-producing fungi or vectors of disease transmission caused by pathogens. For example, the fungal pathogen *Fusarium*, which produces mycotoxins in cereals and nuts, is becoming more prevalent in areas with warmer temperatures and changing levels of humidity (Perrone et al., 2020). In addition, a significant relationship has been observed between the presence of ochratoxin A in grapes and an increase in temperatures (Cervini et al., 2021). Predictive models using scenarios of 2 or 5 ºC increases in temperature in Europe, generate risk maps of corn contaminated with aflatoxins that suggest a higher incidence in southern Europe, especially in Spain (Battilani et al., 2016).

As will be detailed later, temperature has a direct effect on other variables associated with climate change, such as the increase in the concentration of CO_2, the rise in sea levels or the greater incidence of drought and water stress. The joint intervention of all these factors can enhance the dissemination and growth of foodborne pathogens.

3.2 Gas emissions

Since the Earth's atmosphere is composed mainly of nitrogen and oxygen, climatic phenomena are influenced by the water and carbon cycle. CO_2, together with methane (CH_4), nitrogen oxides (NO and N_2O) and ozone (O_3), make up the Greenhouse Gases (GHG) that trap heat in the Earth's atmosphere. Although individually they are present in small amounts, they have a great impact on climate change, since the level of GHG is directly related to atmospheric temperature. GHG have remained for millennia in fossil fuels and biomass, but are being released into the atmosphere by anthropogenic activity. These activities include the transformation of forest lands into agricultural or industrial lands, as well as the use of artificial GHG, such as chlorofluorocarbons. In addition, the current food system is responsible for up to 30 % of GHG emissions, which constitutes an additional incentive to develop agri-ecological and climate-adapted food production (circular agriculture) (Vermeulen et al., 2012).

CO_2 is the most abundant GHG and has a significant impact on global temperature (Hardy, 2003). Due to the close correlation between CO_2 and temperature, an increase in CO_2 levels directly leads to further global warming. In this context, the excessive release of CO_2 into the atmosphere is identified as the main cause of global warming and, consequently, of climate change. The sixth report published by the IPCC contemplates several scenarios of CO_2 emissions from the year 2150. Among them, the low emission scenario stands at about 350 ppm, while the most unfavourable, stands at more than 2000 ppm (IPCC, 2021). These scenarios are associated with temperature increases of between 1.4 and 4.4 ºC (IPCC, 2023).

The continuous increase in the concentration of dissolved CO_2 could affect the survival of animals, microbiota and plants (Huang et al., 2018) (Roufou et al., 2021). Among the main factors, it is known that the concentration of CO_2 influences microbial proliferation, although not all microorganisms are sensitive to this effect (Oliveira et al., 2010). Some stress-adapted bacteria, such as *Listeria* spp. and *E. coli*, are able to passively diffuse CO_2 from the cytoplasm into the cell, allowing them to biosynthesize various small molecules, such as pyrimidines. Therefore, CO_2 could favour its growth and, consequently, increase the risk to public health under the projected climate scenarios (Merlin et al., 2003) (Zhu et al., 2015). In the case of mycotoxin-producing fungi, it has been found that a 2.5-fold increase in the concentration of CO_2 results in an increase in the colonisation of *Aspegillus carbonarius* and in the production of ochratoxin A in the Mediterranean region (Cervini et al., 2021). Similarly, the interaction of temperature (increases of 4 ºC) with high concentrations of CO_2 (>350 ppm) and water stress had a significant influence on the production of aflatoxins by *A. flavus* based on the results of the molecular expression of genes involved in the regulation of mycotoxin biosynthesis (Medina et al., 2015).

Despite the existence of these studies, a more detailed analysis of the kinetics of microbial growth under conditions of increased CO_2 and temperature is necessary to assess the potential risks to human health and food safety associated with bacterial infections.

3.3 Sea level rise

Rising temperatures and CO_2 levels are accelerating glacier melt. Data from 19 000 glaciers around the world estimate that approximately 9000 million tons of ice have been lost between 1961 and 2016, with a notable increase in the rate of loss during the last 30 years (Zemp et al., 2019). Glacial melting, oceanic warming, increased torrential rainfall and insufficient snow accumulation are contributing to sea level rises and increased flood risks (Davenport et al., 2019) (Veng and Andersen, 2020). These conditions are expected to have an impact on sea-level cropping areas and coastal communities, in addition to posing significant challenges for key infrastructures, such as water treatment plants, increasing, in turn, the probability of outbreaks of waterborne diseases. All of these will have to adapt to climate change. According to Hummel et al. (2018), a 2-meter rise in sea level could compromise the operation of 394 wastewater treatment plants that supply approximately 31 million people in the United States.

Likewise, an increase in the frequency of tsunamis associated with sea level rises is expected (FAO, 2020), which could cause the dispersion of pathogenic microorganisms present in sea water to land areas (Engelthaler and Casadevall, 2019).

Therefore, sea level rises caused by climate change threaten coastal communities, increasing the likelihood of salt water intrusion into fresh water resources. In addition, brackish water, a mixture of fresh and salt water, can favour the growth of unique microbial communities, including opportunistic pathogens (IPCC, 2022b).

3.4 Effects of ecosystems and biodiversity

The loss of biodiversity and changes in ecosystems are increasingly linked to the occurrence of infectious diseases and zoonoses (Schmeller et al., 2020) (Bartlow et al., 2021). This relationship is driven by factors such as climate change, habitat degradation and increased contact between humans and wildlife (Schmeller et al., 2020). However, while some studies suggest that greater biodiversity could reduce the risk of disease transmission through a "dilution effect" (Johnson et al., 2015), others argue that greater biodiversity could increase the diversity of pathogens (Morand, 2011). The impact of biodiversity on the risk of foodborne diseases is complex and depends on various factors, including the structure of the ecosystem community, spatial and temporal scales, and trophic interactions (Johnson et al., 2015). Therefore, understanding these relationships is crucial to develop effective strategies to mitigate risks that affect health safety and promote global health (Bartlow et al., 2021). More research is needed to clarify the mechanisms that link biodiversity with infectious diseases, considering realistic patterns of community assembly and changes in ecosystems (Morand, 2011) (Johnson et al., 2015).

3.5 Water stress

Climate change drives the need to use treated wastewater for irrigation, especially in regions affected by water stress. However, this increase in wastewater reuse poses risks related to the elimination of microbiological pathogens in said waters (EU, 2020) (Mishra et al., 2023).

Rising temperatures and extreme weather conditions favour the survival and proliferation of pathogens in treated wastewater. *Salmonella*, for example, can persist longer in warm temperatures, increasing the likelihood of contaminating crops and posing a risk to human health. Enteric viruses, such as noroviruses, hepatitis A virus and rotaviruses, are highly resistant in humid environments and their presence in reused water can facilitate the appearance of outbreaks of gastrointestinal diseases if they are not properly eliminated during purification treatment, mainly in those foods, such as vegetables, berries and vegetables or bivalve molluscs, which are consumed raw or under-cooked (Truchado et al., 2021) (Cuevas-Ferrando et al., 2022). Another aspect to consider is the increase in plastics and microplastics in the reclaimed waters, which promote bacterial colonization and biofilm formation, potentially serving as reservoirs for pathogens (Lu et al., 2022) (Hee Joo et al., 2025).

In addition, climate change exacerbates another critical challenge: the spread of antimicrobial resistance genes. In wastewater treatment systems, antimicrobials and resistant microorganisms can interact with one another, favouring the transfer of resistance to other organisms. This increases the global threat of antibiotic-resistant infections, which already represent a growing public health challenge (Grilo et al., 2021).

Therefore, it is essential to develop and apply advanced purification technologies, such as membrane-based treatments, ultraviolet radiation or advanced oxidation processes, which are capable of efficiently eliminating pathogens and antibiotic-resistant bacteria, in order to prevent their presence in treated water and their dispersion into food. At the regulatory level, stricter standards are required for the surveillance of pathogens and antimicrobial resistance markers in reused water. Only through comprehensive management of the associated risks can it be guaranteed that water reuse is a safe and sustainable strategy in the face of climate change.

Therefore, it is crucial to strengthen purification systems to ensure that the treated water meets strict sanitary standards, or at least is suitable for the intended use after a risk assessment in certain cases (for example, for irrigation) minimizing risks and promoting a sustainable use of water resources in the face of the climate crisis (EU, 2020).

3.6 Extreme weather events

Extreme weather events can affect food safety (Awad et al., 2024). Hurricanes, tornadoes, and wildfires can damage food production and processing infrastructures (e.g., refrigeration equipment), favouring microbial contamination and growth and, therefore, increasing the risk of foodborne disease outbreaks (Duchenne-Moutien and Neetoo, 2021). In addition, displacement and migration of people as a result of natural disasters can increase the likelihood of transmission of foodborne diseases (McMichael, 2015).

Among extreme weather events, floods and drought stand out. Disruptions to power plants or water supply networks related to flooding can affect food storage and preparation. Thus, for example, the power outages and interruptions in cooling systems that occurred during Hurricane Sandy, in 2012, caused a large outbreak of salmonellosis in the north-eastern United States (NYSERDA, 2018). In addition, these events often result in the overflow of wastewater, which leads to the transmission of different microorganisms, such as *Shigella*, norovirus, hepatitis virus or *Cryptosporidium*, either directly or through food (Yavarian et al., 2019). In addition, floods can spread pathogens from agricultural fields and livestock farms (through faeces or animal carcasses) to surface waters and soil (Okaka and Odhiambo, 2018).

Increases in diarrhoeal diseases transmitted through water and food have been reported in India, Brazil, Bangladesh, Mozambique and the United States, after episodes of flooding (Tirado et al., 2010). Floods and storms often cause wastewater to overflow, resulting in the direct transmission, and through food, of noroviruses, hepatitis A viruses and *Cryptosporidium* (Patz et al., 2000) (Boxall et al., 2009) (Semenza et al., 2012b) (Yavarian et al., 2019). A recent example was in Spain during the isolated depression at high level (DANA) of 2024, which affected the Valencian Community, where numerous treatment plants and the sewerage system were damaged, which increased the risk of water pollution and exposure to pathogens.

Disruption of the drinking water supply, which occurs as a result of a flood, can result in inadequate hygiene practices, which also contributes to the transmission of diseases. In addition, the high number of people displaced to assist in the cleaning and reconstruction of the affected areas, together with the interruption of health care, can facilitate the spread of infectious diseases (ECDC, 2021). Thus, there is a frequent increase in reports of cases and outbreaks of diseases transmitted through water and food after episodes of flooding (Tirado et al., 2010) (Gertler et al., 2015). It has been estimated that post-flood disease outbreaks, particularly through contaminated food and water, can increase mortality rates by up to 50 % in the first year after a flood (Weilnhammer et al., 2021).

Droughts, on the other hand, can lead to a decrease in water availability, resulting in increased concentrations of pathogens, as well as heavy metals and other contaminants in the water. Water scarcity can lead to restrictions in public supply and encourage the use of untreated or partially treated water for irrigation, increasing the risk of foodborne diseases (Semenza et al., 2012b). In addition, an insufficient supply of water can lead to a relaxation of hygiene standards in industries and food establishments, increasing the risk of foodborne diseases (Bryan et al., 2020). Sometimes, dry periods boost recreational aquatic activities, increasing exposure to pathogens such as *Leptospira* spp., enterotoxigenic *E. coli* (ETEC), enterococci or parasites (European Climate and Health Observatory, 2024).

4. Impact of climate change on the transmission of foodborne pathogens throughout the food production-consumption chain

The FAO considers that food security exists when "everyone has sufficient physical, social and economic access at all times to safe and nutritious food to meet nutritional needs and food preferences, in a way that allows them to lead an active and healthy life" (FAO, 1996). Climate change influences the safety of food systems as described above due to various direct and indirect effects, such as high temperatures, extreme weather events, air pollution, the increase in vector-borne infectious diseases, the destruction of the ozone layer and water and food pollution (Singh et al., 2023). These effects have clear implications for human health. Food systems include various processes such as the production, processing, distribution, preparation and consumption of food (Schnitter and Berry, 2019). These processes are sensitive to climate and, therefore, are impacted in various ways by climate change (Table 3).

Table 3. Effects of climate change on various components of the food system

Effect of climate change	Components of the food system			
	Production	Processing	Distribution	Preparation and consumption
Increased rainfall	+++			+
Changes in precipitation patterns	+++		+	+
Extreme weather events	+++	++	+++	+

Table 3. Effects of climate change on various components of the food system

Effect of climate change	Components of the food system			
	Production	Processing	Distribution	Preparation and consumption
Sea level rise	++			
Oceanic acidification	+			
Rise in temperature	+++	++		+
Increased CO_2 concentration	+ [a]			
Increased O_3 contamination	+			
Reduced freshwater availability	+++	++		+

[a] An increase in the concentration of CO_2 in the atmosphere can favour the production of some crops. **Source:** (Schnitter and Berry, 2019).

At the primary production level, the food system covers the commercial and non-commercial sectors of agriculture, livestock, fisheries and aquaculture, as well as hunting and gathering of fruits and plants. Climate change is generating a decrease in productivity, which leads to a reduction in the availability and supply of food, with possible repercussions on human health (McMichael et al., 2017). Changes in climatic conditions such as rainfall and temperature have a primary influence on food production through their effects on crop yields (Johansson et al., 2024) and are leading farmers to implement various strategies to adapt to these changes. These include crop diversification, modification of planting and harvesting schedules, and the use of mixtures of varieties for the same crop (e.g. the use of drought-resistant low-yielding varieties and sensitive high-yielding varieties) (Nhemachena and Hassan, 2007).

Although these adaptations enhance the sustainability of food production, the introduction of new adapted crops and innovative agricultural techniques also carries an increased risk of foodborne diseases, with which both the population and health systems may be unfamiliar. In the same way, in the livestock sector, increased temperatures and changes in rainfall patterns affect the distribution and abundance of disease-transmitting vectors, such as viruses, parasites and pathogenic bacteria (Bett et al., 2017). A key strategy to mitigate the effects of the global temperature increase is the incorporation of more heat-resistant breeds. However, this change could increase vulnerability to certain pathogens (Das et al, 2016).

Food processing involves the transformation of raw food inputs into food products prepared for direct consumption. Throughout processing, operations such as washing, disinfection and food preparation are of special importance to provide food safe for consumption (Singh et al., 2023). Evidence suggests that the impacts of climate change can cause interruptions in the stable supply of raw materials or other food additives, and extreme weather events can cause physical damage to industrial facilities (Fanzo et al., 2018).

Distribution is a fundamental part of food security, since it links food products to consumers, which directly supports the capacity for availability and accessibility of food security. Climate change can change food distribution networks through extreme weather events and, in the long term, also progressive climate changes (Palko and Lemmen, 2017).

Finally, from a consumer point of view, global food consumption alone could add almost 1 ºC to warming by the year 2100. However, more than 55 % of the predicted warming can be avoided through simultaneous improvements in production practices, the universal adoption of a healthy diet and the reduction of food waste at the consumer and retail level (Ivanovich et al., 2023).

As a result of climate change, new consumption trends adapted to these phenomena are emerging, such as the incorporation of new food matrices (insects, algae, etc.), the reuse of food industry waste as raw materials for new foods, or the recovery of food waste (Hassoun et al., 2022). Edible insects are emerging as an alternative source of protein, with a lower carbon footprint in the breeding process; however, concerns remain around their microbiological safety. Several studies have revealed high microbial loads in edible insects, both in their fresh and processed state, including the presence of altering bacteria and foodborne pathogens (Garofalo et al., 2017). Therefore, it is essential to apply appropriate conservation technologies (Marín et al., 2020), in addition to the implementation of Hazard Analysis and Critical Control Points (HACCP) systems adapted to these new food matrices. In the European Union, there are already regulations that establish how insects intended for human consumption should be produced (EU, 2015), and they are also evaluated as novel foods by the EFSA.

As for the recovery of by-products or food waste, these products may be susceptible to the development of undesirable microorganisms under inadequate processing and storage conditions. It is therefore necessary to evaluate and control the microbiological risks associated with these by-products, in order to guarantee the health of consumers and promote safe and sustainable recovery.

5. Influence of globalisation on the spread of foodborne pathogens in a context of climate change

Globalisation and climate change are interrelated phenomena that, together, are transforming the patterns of spread of foodborne pathogens worldwide. The intensification of international trade, the increasing mobility of people and goods, and the expansion of supply chains have facilitated the dissemination of pathogens across geographical and health borders. At the same time, climate change is changing environmental conditions that influence the persistence, multiplication and distribution of these pathogens in food and the environment. This combination of factors amplifies the risks to global food safety, favouring the emergence of outbreaks in new regions, hindering the traceability of infectious outbreaks and challenging traditional control systems.

International trade and human mobility are the defining characteristics of globalisation, a phenomenon that increases the risk of foodborne diseases transmission (Todd, 2013). Today a greater variety and volume of goods are shipped to more destinations, and more people travel long distances more frequently, coming into contact with more individuals and products than at any other time in history, thus creating new opportunities for the spread of foodborne microorganisms. The introduction of livestock, companion animals, aquatic animals and wildlife into new geographical areas can cause the spread of microorganisms to other places, while introduced animals can be infected with endemic microorganisms, despite existing international regulations or guidelines to minimize these risks. For example, the growing global demand for meat is driving an increase in the production and trade of this food and, at the official control level, standardized tests related, among other things, to the detection of *Trichinella* are systematically carried out.

With regard to the movement of people, it is estimated that, in 2020, 281 million individuals (3.6 % of the world's population) migrated outside their country of origin (IOM, 2024). The migration of people also causes the movement of pathogens transmitted through food to new geographical areas (Robertson et al., 2014). Among the food pathogens that are most easily spread among people are parasites, such as *Taenia saginata* (highly prevalent in Africa), *Fasciolopsis buski* (Asia), *Opisthorchis viverrini* and *Clonorchis sinensis* (Southwest Asia), *Taenia solium* (South Asia), *Opisthorchis guayaquilensis* (South America), *Echinococcus granulosus* (Middle East), and *Diphyllobotrium* spp. and *Felineus opisthorchis* (Eastern Europe) (Robertson et al., 2014).

In addition, people who migrate bring their food and traditions with them, influencing local preferences and eating habits (Broglia and Kapel, 2011). Thus, there is a growing number of consumers who demand exotic products (e.g., crocodile meat) or seasonal products throughout the year (e.g., strawberries during the winter), which are now easily available at our tables due to international trade all year round (Macpherson, 2013).

In relation to livestock, a good example of the spread of diseases related to the transport of animals is that of *Fasciola hepatica*, a trematode that has been established almost globally as a result of the colonisation of other continents by European countries and the consequent introduction of herbivorous animals from Europe into new geographical areas (Mas-Coma et al., 2009). Likewise, in many countries there was a large increase in pig trade between 1997 and 2007, which saw a simultaneous increase in cases of teniasis, trichinellosis and toxoplasmosis (Robertson et al., 2014). In turn, it has been found that the incidence of bovine cysticercosis increased from 4 to 38 % after the start of the import of live cattle to Israel (Meiry et al., 2013).

The international transport of companion animals (for holidays, competitions, humanitarian missions, etc.) also represents a risk of introduction of pathogens that can be transmitted through food, such as, for example, *E. multilocularis*, *E. granulosus* and *Toxocara* spp. (Macpherson, 2013). Likewise, wildlife animals are important reservoirs of pathogenic microorganisms (Jones et al., 2008), and their movement (feeding, introduction into hunting grounds, restocking, zoos or pets) is a risk factor for the appearance of emerging diseases (Robertson et al., 2014).

Regarding the transport of food, it should be noted that there are great differences between exporting and importing countries in terms of production methods, sanitation, hygiene, and agricultural or livestock practices. As a result, the types and levels of foodborne pathogens vary across geographical regions (Doyle and Erickson, 2008). With regard specifically to meat and fish, these are foods that can transmit pathogenic microorganisms if adequate storage temperatures are not respected (Donoso et al., 2016). Current trends in the consumption of exotic products have led to the increasing incorporation of game meat in exclusive restaurants, both in Europe and the United States, while it is imported to meet the needs of immigrant communities in various countries, thus generating a significant risk if good hygiene and handling practices are not observed in these establishments. In addition, it is worth highlighting the current tendency to consume raw or undercooked fish (Robertson et al., 2014).

In the case of fruits and vegetables, the main infectious agents they transmit correspond to microorganisms present in fresh products. The transmission potential has increased due to the tendency to consume products of organic origin (Li et al., 2025). Regarding spices and herbs, globalisation has made these products available throughout the year in a large number of countries, and outbreaks of food transmission due to their consumption have been detected in different geographical areas (Zweifel and Stephan, 2012).

6. Digitalisation as a strategy for the monitoring and management of the risk of foodborne pathogens associated with climate change

As detailed in the previous sections, climate change has generated changes in ecosystems that affect food safety and the spread of foodborne pathogens. In this context, digitalisation has become a key tool for monitoring and managing risk, allowing the collection, analysis and modelling of data for a more efficient response to emerging threats. One of the most promising approaches in the digitalisation of food safety is the use of epidemiological surveillance platforms based on Big Data. These tools allow the collection of data from various sources, such as analysis laboratories, public health databases and environmental monitoring. Through the use of advanced algorithms, these systems can identify correlations between climatic conditions and the occurrence of disease outbreaks, thus facilitating decision-making based on scientific evidence. The availability of epidemiological and environmental surveillance databases means that trends in weather patterns can be analysed, by obtaining real-time risk prediction maps that include different scenarios and preventive measures to be adopted on health programs and official food control (Mirón, 2017).

The use of digital strategies makes it possible to identify epidemiological patterns and predict possible outbreaks before they become public health crises. Technological advances have allowed the development of digital systems based on Artificial Intelligence (AI), Internet of Things (IoT) and Big Data, which offer innovative solutions for the surveillance of pathogens in food. These systems integrate advanced sensors capable of detecting biological contaminants in real time, with the ability to immediately transmit data to centralised platforms. In this way, it is possible to analyse large volumes of information and generate early warnings that allow rapid and efficient intervention (Karanth et al., 2023a).

Another key aspect in the digitalisation of pathogen risk management is the use of AI-based predictive models. These models can evaluate multiple environmental and biological variables to estimate the behaviour of microorganisms in different climate scenarios. The development of microbiological risk assessments is increasingly oriented to the incorporation of molecular information, since climate change can produce modifications in the genetic profile of foodborne pathogens. The quantification of risk due to climate variables is complex, due to the variability in their impact on the persistence and virulence of food pathogens (Katsini et al., 2022). By way of example, the increase in temperatures can induce the horizontal transfer of genes and mobile genetic elements of resistance, promoting the increase in the incidence of antimicrobial resistant pathogens (MacFadden et al., 2018). On the other hand, there are studies based on Machine Learning algorithms that can predict changes in the genetic patterns of *E. coli* and *Salmonella* taking into account variables associated with climate change (Buyrukoglu et al., 2021) (Karanth et al., 2023b) (Roufou et al., 2024).

In addition, the use of digital platforms has facilitated communication between the different entities involved in food safety. Mobile applications and cloud-based systems allow immediate notification of relevant findings, promoting a coordinated response between producers, health authorities and food distributors. This is crucial in a context of climate change, where environmental conditions can vary unpredictably, increasing the likelihood of unexpected outbreaks.

The automation of inspection and quality control processes has also been enhanced by digitalisation. The use of drones equipped with thermal cameras and spectroscopy allows the evaluation of contamination in crops and water bodies without the need for manual sampling (Jin et al., 2021). Likewise, the implementation of artificial vision systems in food processing plants contributes to the rapid detection of irregularities in production (Jia et al., 2020).

As climate change continues to affect the ecology of pathogens, the implementation of digital solutions becomes increasingly relevant to ensure food safety and protect public health. However, despite the benefits of digitalisation in pathogen risk management, there are challenges that need to be addressed. The standardisation of data protocols, cybersecurity and accessibility to these technologies in developing countries are some of the challenges to be overcome. Effective integration of these systems requires investment in infrastructure and staff training, in addition to cooperation between the public and private sectors to ensure their effective implementation.

Conclusions of the Scientific Committee

Climate change can have an impact on food safety and public health due to the proliferation and spread of foodborne pathogens. Alterations in weather patterns, such as increased temperatures, changes in rainfall and the greater frequency of extreme weather events, have modified the distribution and persistence of microorganisms, favouring their expansion to new geographical areas and increasing the risk of diseases transmitted through food.

One of the main challenges in the context of climate change is the remarkable adaptability of pathogens to varying environmental conditions. Various studies have shown that microorganisms such as *Salmonella*, *Campylobacter*, *Escherichia coli* and species of the genus *Vibrio* tend to be more prevalent in environments with high temperatures, since heat can favour their growth, survival and ability to infect. On the other hand, the variability in rainfall and environmental humidity has benefited the persistence and dissemination of other agents, such as enteric viruses and certain parasites, by facilitating their transport in surface waters or their survival in humid soils.

In addition, changing environmental conditions may contribute to increased antimicrobial resistance globally. Environmental stress (caused by factors such as extreme heat, drought or pollution) can act as a selective pressure that favours the survival of more resistant microbial strains, making it difficult to eliminate them through conventional treatments and complicating their control throughout the entire food chain.

In this scenario, the globalisation of agri-food systems has intensified the impact of climate change on global food safety. The expansion of international trade, together with the growing demand for fresh, exotic or minimally processed products, has multiplied the routes of transmission of pathogens, facilitating their introduction into new regions. Practices such as the mass transport of animals and food, the use of wastewater in agriculture, and the adoption of new food consumption patterns, have increased the population's exposure to emerging and re-emerging pathogens, and with it, the risk of outbreaks on an international scale.

To mitigate these risks, it is crucial to reinforce epidemiological surveillance systems by using advanced technologies. The implementation of digital platforms for risk management has made it possible to improve communication and coordination between the different actors in the food chain, facilitating rapid responses to health emergencies.

Likewise, the adaptation of food safety regulations and protocols is essential to face the new challenges derived from climate change. Strategies such as the promotion of sustainable agricultural practices, the monitoring of water used in irrigation and the reinforcement of biosecurity measures in livestock production can significantly reduce the incidence of foodborne diseases.

Climate change not only affects food safety in the short term, but also poses long-term challenges in terms of resilience and sustainability of food systems. Ongoing research is critical to better understand the relationship between the climate and pathogens, as well as to develop innovative solutions that minimize their impact on human health. International and multidisciplinary collaboration will be key in the formulation of effective policies for risk mitigation and adaptation to a changing environment.

Finally, educating and raising public awareness of the food risks associated with climate change are fundamental tools to promote responsible consumption habits and ensure safer and more sustainable food systems in the future. Preparing for natural disasters, strengthening health infrastructure and investing in microbiological control technologies are priority measures to reduce the vulnerability of communities to these environmental changes. In this context, microbiological control refers to the set of techniques and technologies aimed at detecting, eliminating or inhibiting the proliferation of pathogenic microorganisms in food, water and contact surfaces. This includes methods such as advanced filtration, disinfection by ultraviolet radiation, ozone or chlorination, as well as the development of real-time monitoring systems, biosensors and other tools that allow for the rapid identification and response to the presence of microbiological contaminants in environments critical to public health.

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