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Climate change and its implications for food safety and spoilage

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ABSTRACT

Background: Climate change constitutes a complex challenge posing an urgent threat to our planet and life and creating an entirely different way of conceptualising the world and our chances to provide safe food within it. There are currently numerous studies dealing with the potential effect of increased temperature, extreme weather events and cascading events on food safety and subsequently human health. In contrast to food safety, the available data on the impact of climate change on food quality, including food spoilage, are very limited.

Scope and approach: This paper presents an overview of the potential impact of climate change on both food safety and microbial spoilage at various stages of the food chain. Among the different hazards related to climate change, mycotoxin and marine biotoxin contamination, environmental residuals derived from various anthropogenic activities and zoonosis diseases are identified as climatic-driven emerging risks to human life and discussed further in this paper. Global warming is projected to affect all microorganisms, including spoilage bacteria and fungi. Hence, this paper also discusses the potential increased risk of microbial spoilage for bulk dried foods and non-refrigerated processed foods which could be high susceptible to climate change in relation to growth of spoilage organisms.

Key-findings and conclusions: The paper concludes that climate change requires multidisciplinary approaches to gain in-depth knowledge and identify potential emerging risks. In addition, this paper goes beyond food safety and addresses an overlooked aspect of climate change, namely the microbiological spoilage of foods that may require a high level of preparedness by both the food industry and policy makers.

1. Introduction

Over the last decades, climate change has received increasing attention since it poses an urgent threat to our planet's ecosystems and human societies. Climate change has been defined as '*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability, observed over comparable time periods*' (United Nations, 1994). According to the Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC), the average increase in global surface temperature, driven by four scenarios for population, economic growth and carbon use is predicted to range from 1.7 to 4.8 °C till the end of the 21st century (IPCC, 2014).

Climate change however, does not only imply increased average global temperature. Additional effects of climate change include extreme weather events and natural disasters, such as floods, droughts, hurricanes, tsunamis etc., increased frequency of heavy precipitation events, extended dry periods, acidification of water and potentially rising sea levels. The above-mentioned pathways of climate change can affect agriculture, fishery and livestock production (FAO, 2008). Since food production is related to all these different sectors, it can be directly and/or indirectly affected by climate change at worldwide levels. Due to their importance and complexity, development of climate change along with its implications for food safety and quality are explained in more detail below.

According to FAO, climate changes may affect among others the survival and growth of environmental pathogens, the sources and ways of transmission, as well as the food matrix and subsequently human health (FAO, 2008). Therefore, climate related changes are presented based on the epidemiologic triad perspective, namely interactions among agent, environment and host. In addition, the role of vectors in the various transmission of pathogens is also described.

While the impacts of climate change on primary food production and the consequences on food security are well documented, the climate change consequences on food safety have received less attention (FAO, 2020). Likewise, there is still limited knowledge on how climate change

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may affect food spoilage, since only a few studies provide scientific evidence on microbial spoilage during distribution and storage due to climate change.

Hence, this article provides an overview of climate change implications for food safety including effects on mycotoxin and biotoxin contamination, environmental residuals, food- and water-borne diseases while discusses the potential impacts of climate change on microbial spoilage (Fig. 1).

2. Impact of climate change on agriculture and associated food safety issues

According to World bank data in 2016, agriculture sector, including arable farming and horticulture, possess almost the 40% of the terrestrial surface. Therefore, it is expected that the agriculture sector will be probably the most vulnerable to climate changes compared to livestock production or marine sector (Miraglia et al., 2009). More specifically, among the different predictive pathways of climate change, increase of temperature, droughts, CO_2 enriched atmosphere and extreme precipitations with altered patterns will directly affect agriculture and subsequently food safety.

Impact of climate change will be notable both for biotic populations and abiotic factors contributing to agriculture. Microbial populations of insects, pests and other vectors as well as microbial population of soil will be affected by climate changes and subsequently will affect prevalence of microorganisms, such as fungi and viruses. Abiotic factors, such as air pollution, nutrient deficiencies and extreme temperature will affect soil quality, plant health and crop productivity (FAO, 2008). Therefore, food safety issues related to the risk of elevated human exposure to higher mycotoxins and pesticides residues may arise (WHO, 2019).

2.1. *Toxigenic fungi and mycotoxins*

Mycotoxins are naturally produced as metabolites by a variety of toxigenic fungi grown on several crops. Mycotoxins have severe adverse effect both on human and animal health. The severity of those effects depends on the specific mycotoxin and its dose. Exposure to mycotoxins causes both acute effects, such as death and chronic diseases including different various types of cancer. The most characterised mycotoxins are produced by the genera *Aspergillus, Fusarium* and *Penicillium* (CAST, 2003). Among the different mycotoxins, aflatoxins have the highest acute and chronic toxicity, including genotoxicity, carcinogenicity and immunotoxicity. Human dietary exposure to mycotoxins can occur both in direct and indirect way; directly through the consumption of contaminated crops and indirectly through the consumption of products of animal origin derived from livestock which has been fed with contaminated feed.

With the foreseen climate change, particularly temperature and drought, wheat and maize arable areas are expected to change and aflatoxin contamination is expected to become more prevalent. Taking into account that a temperature increase of 1 °C can lead to a 6% reduction of the average global yields of wheat (Zhao et al., 2017), implications for food security should be expected. Hence, the combination of increased aflatoxin contamination and reduced yields may lead to increased intoxications particularly especially in developing countries. Therefore, aflatoxin contamination is considered an emerging food safety issue. A more detailed review on the impact of climate change on mycotoxins is provided in the second paper of this special issue, entitled '*Feed to fork risk assessment of mycotoxins under climate change influences - Recent developments*'' (Chhaya, O'Brien, & Cummins, 2021).

2.2. *Soil quality and degradation*

Soil characteristics are susceptible to climate change. However, due

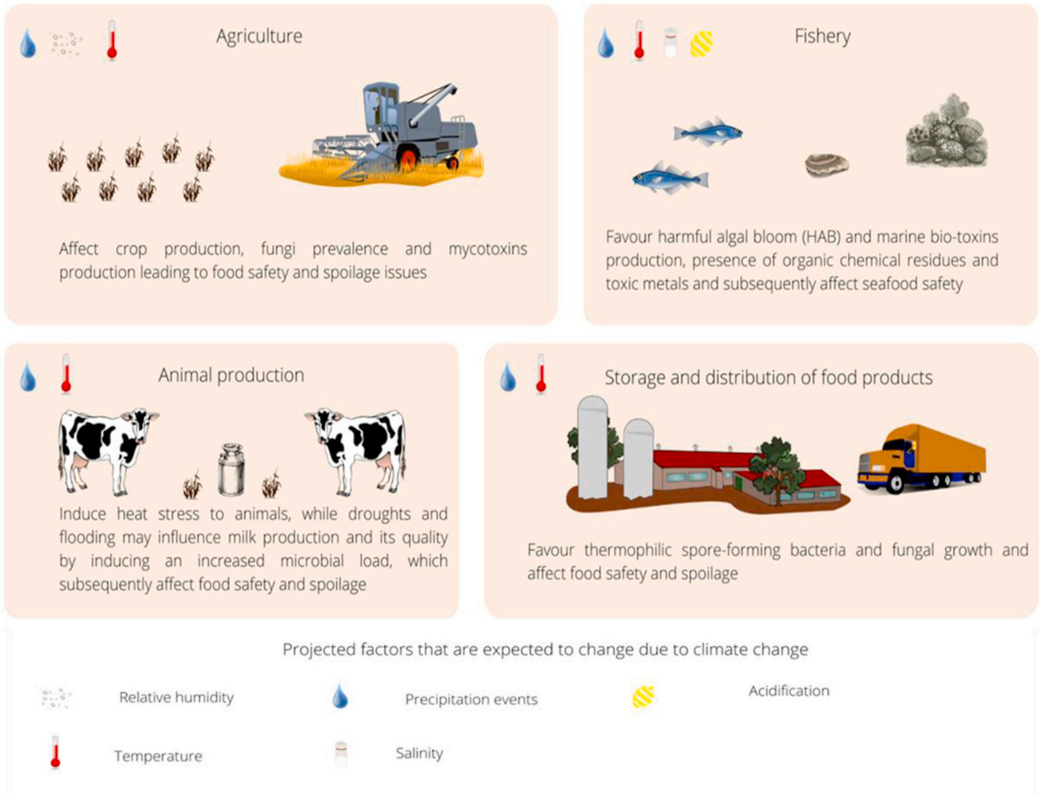

Fig. 1. Overview of climate change implications for food safety and food spoilage at various stages of the food chain. Factors that are expected to change due to the projected climate change along with their potential impacts on food safety and food spoilage.

to the complexity and the uncertainty of the interaction between minerals, chemicals, soil microbial populations and weather events, the assessment of the impact of climate change on soil quality and plant growth remains challenging (Sparks, 2001). A better understanding of these interactions adopting a multidisciplinary approach is required, for a realistic evaluation of the implications of climate change in soil quality to take place.

A possible alteration in transfer and bioavailability of the soil trace elements to plants due to climate change has already been identified (FAO, 2008). In addition, degradation of soil quality in Europe due to erosions and leaching, caused by extreme precipitations, has already been demonstrated (Smith et al., 2005). Erosions and leaching driven by altered precipitation patterns and increased temperature often lead to losses of soil minerals (Miraglia et al., 2009).

As plant uptake is based on the interaction between soil factors and microbial populations, the impact of climate change on soil microbial population is of great concern. Distribution and bioavailability of essential elements can be affected by microorganisms. Therefore, plant growth may potentially be affected by a significant loss of microbial biodiversity, due to increases in nitrogen and phosphorus (Dai et al., 2018). In the same vein, deficiency of nutrients in soil may reduce the resistance of plants to pests, insects and plant diseases (FAO, 2008). Hence, plants might become more vulnerable to fungi colonisation and mycotoxins production. The ability of crop to grow is strongly correlated to the increased temperature and drought (Godfray et al., 2010). Disturbances in abundance and diversity of soil microbial population (fungi and bacteria) caused by aridity (Bahram et al., 2018; Maestre et al., 2015) can limit the capacity to support plant growth (Jing et al., 2015).

Climate change will lead to modifications of arable areas suitable for growing crops owing to soil quality, variations in the seasons and changes in the plant pests. Water deficiency, frequency and intensity of extreme weather events promote modifications of the biogeographical agricultural scenario of cultivated plants. Many studies substantiate the belief that arable areas and crop yields are expected to decrease in Southern Europe, since the Mediterranean region is expected to be one of the most vulnerable areas to climate change (Giorgi & Lionello, 2008). On the contrary, crop yields and areas suitable for crop production are expected to expand in Northern Europe (Maracchi, Sirotenko, & Bindi, 2005; Messerli, Grosjean, Hofer, Núñez, & Pfister, 2000; Olesen & Bindi, 2002). Maize production is a case in point, since it is expected to be increased by 30–50% in Northern parts of Europe (WHO, 2007).

2.3. Pesticides and pesticides residues

Except from the above-mentioned global warming effect on soil degradation, mycotoxins and crop yields, the greater frequency and intensity of extreme weather events are expected to affect crop pests' populations. Overall, the ability of insects to overwinter, including their geographical distribution, reproduction and abundance is expected to be influenced by climate change (Cynthia Rosenzweig, Iglesias, Yang, Epstein, & Chivian, 2001). According to Rosenzweig and colleagues, alterations in transmission dynamics of pests, insects and plant diseases will affect both yield production and food safety. The authors contended that a change in precipitation patterns may have a higher impact on pests and their interactions with crops, compared to the annual total precipitation.

The precise impact of climate change on insects and plant pathogens is still uncertain (Petzoldt & Seaman, 2005). However, a wide body of evidence suggests that an overall increase in the number of outbreaks of a wider variety of pests, insects and plant pathogens should be expected. Attacks of insects can influence both plants and fungal distribution and life cycle, by inducing lower stress resistance and mechanical damage on kernels and fruits, which subsequently become more susceptible to fungal growth (Tirado, Clarke, Jaykus, McQuatters-Gollop, & Frank, 2010). Therefore, increased pest damage at an early stage of crop development favours growth of toxigenic fungi and mycotoxin production.

According to FAO, host plant susceptibility to pests, number of pests generations per year, pest development rates, as well as pest mortality during winter months may be affected by climate change (FAO, 2005a; 2005b). In addition, increased temperature and extended dry periods may make existing chemical and natural pesticides inappropriate for use, since pesticides may be degraded faster in higher temperature or exhibit limited activity in dry conditions (Bailey, 2004; Muriel et al., 2000).

As it is discussed above, modifications of arable areas suitable for growing crops, temperature increase and changes in the plant pests are expected due to climate change. In order to compete with these growing crop yield challenges, an increasing use of pesticides may be necessary. Subsequently, if good agricultural practices do not meet, increased levels of pesticides residues in crops and food products could be expected. Therefore, the risk of human exposure to elevated pesticides residuals rises concerns that is expected to become more prevalent in the forthcoming years. These pesticide use patterns have a devastating effect on protective predators and increase the resistance of pests (Rosenzweig, Yang, Anderson, Epstein, & Vicarelli, 2005). Furthermore, it is anticipated that pesticides abuse will directly threaten farmers' health or indirectly the consumers' health after consumption of high-level contaminated food products (Tirado et al., 2010).

3. Impact of climate change on marine and associated food safety issues

Although there is about 100-fold less marine biomass than terrestrial biomass, marine biomass covers almost 70% of the surface of the Earth (Bar-On, Phillips, & Milo, 2018; Cavicchioli et al., 2019). Marine phytoplankton performs half of the oxygen production and half of the global CO_2 fixation through photosynthesis (Behrenfeld, 2014). Hence, any climate change alteration that influence marine biomass could suffer considerable consequences.

In the upcoming years climate change consequences may impair seafood safety and subsequently human health, since both chemical and microbiological risks may arise. Among the potential emerging risks marine bio-toxins, organic chemical residues and toxic metals have been identified as the most important ones. Among the microbiological risks, water pathogens such as *Vibrio* spp., are of great concern. However, these microbiological risks lead to waterborne diseases and therefore are discussed in detail in section 5 (see section 5.2.3).

3.1. Harmful algal bloom and marine bio-toxins

The proliferation of microalgae in densities that cause damages to the environment and threaten aquatic life as well as human health, is described under the term "harmful algal blooms" (HAB) (Anderson, 1995; Erdner et al., 2008).

Some harmful algal (HA) species produce toxins especially during blooms. These toxins lead to human intoxications, since they can accumulate in filter-feeding fish and shellfish, such as mussels, and be transferred to upper levels in the food chain and finally reach humans. Ciguatera fish poisoning (CFP) is the most common seafood poisoning associated with the consumption of food contaminated with HAB toxins. Additionally, amnestic shellfish poisoning (ASP), azapsiracid shellfish poisoning (AZP), neurotoxic shellfish poisoning (NSP), paralytic shellfish poisoning (PSP) and diarrheic shellfish poisoning (DSP) are also included in the potential illnesses related to these toxins. All the above-mentioned human intoxications cannot be prevented by normal food preparation procedure, since these toxins are generally heat- and acid-stable as well as tasteless and odorless (Fleming et al., 2006), thus non-detectable by human senses.

The HA species responsible for these illnesses belong to two functional groups of phytoplankton; dinoflagellates and diatoms. Increased water temperature, sunlight, wind direction and salinity favour the growth of certain microalgae, including dinoflagellates and diatoms. Distribution, abundance and growth of some genera of dinoflagellates have been reported to be highly temperature dependent. Therefore, ocean warming is expected to increase their abundance (Kibler, Litaker, Holland, Vandersea, & Tester, 2012). For instance, diversity and abundance of *Cambierdiscus* and *Fukuyoa* species in Gulf of Mexico and along the U.S. southeast Atlantic coast are expected to increase due to rising water temperature (Kibler, Tester, Kunkel, Moore, & Litaker, 2015).

In the same study a possible expansion of their geographical range is also projected. These projections are in line with the reported outbreaks of ciguatera fish poisoning (CFP), caused by *Cambierdiscus*, *Fukuyoa* and other species that produce ciguatoxins, which have been expanded geographically over the last few decades (Friedman et al., 2017). CFP reported cases have been also expanded in time, especially during an extreme weather event. During the El Niño phenomenon, the easterly trade winds that blow across the equatorial Pacific weaken and sometimes reverse leading to an anomalously warming of the tropical Pacific (Marques, Leonor, Moore, & Strom, 2010). As a result, this phenomenon leads to coral mass bleaching. The dead coral provides a new surface to *Cambierdiscus toxicus* for colonisation and growth. According to Chateau-Degat and colleagues, *Cambierdiscus* spp. cell density rise after approximately 13–17 months and increased cases of CFP have observed to be reported 20 months after the El Niño event (Chateau-Degat et al., 2005).

3.2. *Organic chemicals residues*

Climate related factors such as temperature, salinity, UV radiation and oxygen, may affect the toxicity of different organic chemicals (OCs) and subsequently their bioaccumulation in both marine biota and human food chain. The nature of these effects and to which extend this alteration will take place depends on both the chemical contaminant and the life stage of the affected organisms (Marques et al., 2010).

Temperature appears to affect global distribution and toxicity of OCs. Many studies have highlighted the fact that toxicity of many OCs rise with temperature, since the rates of uptake and excretion increased with temperature and it can be proven lethal for crabs (*Chasmagnathus granulata*), shrimp (*Palaemonetes pugio*) and fish (*Fundulus heteroclitus*) (DeLorenzo, Wallace, Danese, & Baird, 2009; Maruya, Smalling, & Vetter, 2005; Monserrat & Bianchini, 1995). Another climatic factor of concern is the hypoxic conditions. Toxicity of different contaminants, such as tetrachlorodibenzodioxin, can be increased under hypoxic conditions (Prasch, Andreasen, Peterson, & Heideman, 2004) and may severely affect sensitive species. In a study conducted in the Gulf of Mexico it was found that survival of brown shrimp *Penaeus aztecus* decreased when it was exposed to polycyclic aromatic hydrocarbons (PAH) under hypoxic conditions (Zou & Stueben, 2006). However, organic chemicals, such as PAHs, are potentially mutagenic and carcinogenic not only for aquatic organisms but also for humans (Miraglia et al., 2009). Therefore, exposure of aquatic organisms and fish to OCs is a cause of concern, since they can be transferred to upper levels of food chain.

According to Noyes and colleagues, salinity may modulate toxicity of contaminants and physiological functioning of species (Noyes et al., 2009). Although the effect of salinity on the uptake, bioaccumulation and toxicity of OCs have been investigated, no consistent trend for most of OCs has been identified. On the contrary, toxicity of organophosphate insecticides appears to be an exception as it is increased with increased salinity (Marques et al., 2010).

3.3. *Toxic metals*

Exposure to toxic compounds such as cadmium, lead and mercury, chromium, copper, nickel and zinc poses substantial health risks when exceeding their threshold concentrations. In particular cadmium, lead and mercury are considered as the most crucial ones for seafood safety. Among the climatic factors, temperature, hypoxia and salinity are of a great concern since they affect the fate and toxicity of toxic metals and subsequently threaten marine and human life.

Increased uptake and bioaccumulation of mercury is known as a temperature dependent procedure for many aquatic organisms. Ocean warming facilitates mercury methylation and the subsequent uptake by fish and mammals. A study that modelled the transfer of methyl mercury found that for every 1 °C increase in water temperature the methyl mercury uptake was increased by 3–5% (Booth & Zeller, 2005). Based on their 100 years-scenario, authors concluded that organisms higher up in the food chain are expected to face higher accumulation of methyl mercury owing to increased temperature.

In addition, hypoxia related to climate change, leads to a more rapid biomethylation of mercury and thus pose an increased risk for seafood safety (Gianguzza, Pelizzetti, & Sammartano, 2000). Mercury uptake by phytoplankton, fungi, bacteria, molluscs and crustaceans is also influenced by the alterations on the precipitation and steam flow patterns which influence salinity levels of coastal systems. The increased toxicity of mercury to the mangrove clam *Polymesoda erosa* at higher salinities (10–30 ppt) has been previously reported (Modassir, 2000). Similarly, higher salinity has been found to increase acute toxicity of metal ions copper and zinc in *Tigriopus japonicas* (Park et al., 2014).

Ocean warming can also be related to toxicity and uptake of cadmium. A study that investigated the impact of water temperature on the uptake of several toxic metals, such as copper, zinc, lead and cadmium revealed that the toxicity of cadmium in the juvenile crayfish *Orconectes immunis* acclimated faster at increased temperatures (Khan et al., 2006). Moreover, the uptake and accumulation of lead from *Mytilus edulis* has been found to have a positive correlation with increased temperature (Mubiana & Blust, 2007).

Given that hypoxia, salinity and ocean temperature affect the fate and toxicity of metals, bioaccumulation of toxic metals in fish and fish mammals is expected to indirectly influence human exposure to these toxic compounds. Therefore, an extensively monitoring system should be in place to control the bioaccumulation of toxic metals.

4. Impact of climate change on animal production and associated food safety issues

The potential impact of climate change on the agriculture and marine sectors have received increased attention in the last decades. On the contrary, the impact of climate change on animal production has not received the same recognition. Given the fact that by 2050 global demand for livestock products is expected to be doubled (Rojas-Downing, Nejadhashemi, Harrigan, & Woznicki, 2017), it is paramount to discuss the potential impact of the impending climate change on the livestock sector.

Among the different climatic factors, temperature and precipitation events play a key role to the limitation of livestock production. Both climatic factors are capable of affecting animals directly and indirectly. For instance, rising temperature can induce heat stress to animals, while droughts and flooding may influence milk production and its quality due to shifts in the quality and availability of crops and water (van der Spiegel, van der Fels-Klerx, & Marvin, 2012).

4.1. *Livestock production and husbandry practices*

With the foreseen climate change husbandry practices are expected to be altered. In an attempt to fight these increased infections a higher number of antimicrobial treatments may necessitate. Therefore, an expanded level of veterinary drugs' residuals in food of animal origin could be expected (Tirado et al., 2010). Subsequently, antimicrobial resistance is expected to rise. Given this alteration in the husbandry practises, infectious animal diseases may transmit faster within sheds and subsequently, rise concerns related to food safety (see section 4.2).

In the same vein, livestock production may also become susceptible to climate change and a possible shift to livestock breeds that can compete better with potential stress, such as heat stress, is expected.

4.2. Increased antimicrobial resistance

Heavy precipitation events and increased temperature is expected to alter the transmission pathways and survival of pests. A more detailed discussion on the impact of climate change on pests is provided in section 5 (see section 5.1). Moreover, increased temperature is expected to influence the proliferation of pathogens both in animal feed and husbandry environment (see section 5.2 & 5.3) and lead to an increase in animal and zoonosis diseases (Rojas-Downing, Nejadhashemi, Harrigan, & Woznicki., 2017). In an attempt to fight these increased infections a higher number of antimicrobial treatments may necessitate. Therefore, an expanded level of veterinary drugs' residuals in food of animal origin could be expected (Tirado et al., 2010). Subsequently, antimicrobial resistance is expected to rise. Given the fact that microorganisms are projected to expand their geographical range and the limitations in the effectiveness of antimicrobials in many sectors (FAO, 2018) due to climate change, challenges related to antimicrobial resistance may exacerbate (FAO, 2020).

Expect from the geographical expansion, temperature is another factor that could cause an increase of antimicrobial resistance. Bacterial growth and their resistance to antimicrobials, have been known to be affected by temperature. According to a study conducted in the United States, global warming was positively correlated with the increase of antimicrobial resistance of three common pathogens (MacFadden, McGough, Fisman, Santillana, & Brownstein, 2018). Authors highlighted the fact that even though correlation between temperature and antimicrobial resistance has been proven, less are known about the mechanism behind this observed association. A proposed hypothesis could be that plasmids, containing genes associated with the antimicrobial resistance, transmitted faster under elevated temperature.

However, scientific evidence on the impact of global warming on microbial resistance and the associated mechanism is lacking. Therefore, safety management systems and extensive monitoring should be in place to control both veterinary drug residuals and antimicrobial resistant microorganisms.

5. Impact of climate change on zoonosis diseases and associated food safety issues

Water- and food-borne diseases are tremendously important since they lead to high morbidity and mortality rates. World Health Organisation (WHO) estimated that water- and food-borne diseases occurring from bacteria, viruses and protozoa caused 420,000 deaths in 2010, resulting in 33 million disability-adjusted life years (DALYs). Among the reported deaths, more than 50% (230,000) caused from diarrhoeal disease agents (WHO, 2015).

Climate change has been identified as a potential driver of increasing bacterial, viral and pathogenic contamination of water and food. Several climatic factors, such as temperature, humidity and extreme weather events could alter the feature of survival and transmission patterns. Larger outbreaks caused by pathogens that are highly persistent in the environment (eg. *Mycobacterium avium*), such as temperature or/and pH resistant (eg. *Salmonella* spp.) or have low infectious dose, such as *Shigella* spp. enterohaemorrhagic *Escherichia coli*, *E. coli* O157:H7, enteric viruses and parasitic protozoa are more likely to occur (FAO, 2020). Therefore, risks related to water and food infection diseases may increase (Hall, D'Souza, & Kirk, 2002; Rose et al., 2001) and new risks may emerge (EFSA, 2020).

Before elaborating further about, the influence of climate change on water- and food-borne infection diseases, it is paramount to provide some information on the role of vectors, as well as on the correlation between them and climate change.

5.1. Vectors

Variations in precipitation events and temperature could significantly influence seasonality, range and incidence of zoonosis diseases transmitted through vectors, since the latest are extremely sensitive to climatic factor changes (FAO, 2008). Multiple environmental factors have demonstrated a positive correlation with the alteration of the transmission routes of vectors (McIntyre et al., 2017). Given the foreseen climate change, the impact of these environmental factors on vectors may increase.

Global warming and subsequently milder winter periods have been found to favour both the survival of different insects, such as flies that carry *Campylobacter*, and their geographical range expansion (Cousins, Sargeant, Fisman, & Greer, 2019). This expected expansion in geographical range, due to climate change, could lead to modification of areas that are considered disease-free. Likewise, decreasing precipitation events have been proven to favour arthropod vectors range expansion, such as ticks (Trape et al., 1996). Hence, new "thermal niche'' along with different climatic scenarios should be combined into predictive models, which will allow for the prevention and mitigation measures to be taken.

5.2. Correlation between climatic factors and water- and food-borne diseases

Climatic factors such as extreme heat or cold, droughts, precipitations, storms, wind and surges have been increased not only in number, but also in intensity over the past few decades (IPCC, 2014; Kron, Löw, & Kundzewicz, 2019) and they could promote pathogens proliferation by creating suitable conditions for their survival and multiplication (Lake, 2017; Semenza et al., 2012; Tran, Jassby, & Schwabe, 2017). Many studies have investigated the association between natural disasters, such as earthquakes, or heavy precipitation events leading to flooding, and infectious diseases. For instance, a *Salmonella enterica* outbreak was reported as a consequence of an earthquake event, while a *Campylobacter jejuni* outbreak was reported after flooding. Both cases had been identified as post-event disease outbreaks (Harder-Lauridsen, Kuhn, Erichsen, Mølbak, & Ethelberg, 2013; Nigro et al., 2016). In addition, a seasonal trend on confirmed cases has been observed for many food-borne pathogens, such as *Campylobacter, Salmonella, Escherichia* and *Listeria* spp. (EFSA, 2018). However, the observed seasonality of the confirmed cases may alter due to climate change. Therefore, an in-depth knowledge of how climatic factors could affect pathogen transmission and survival is still required in order to improve the design and implementation of a sanitation programme.

5.2.1. Campylobacteriosis

Campylobacteriosis is an infectious diarrhoeal disease caused by *Campylobacter* spp. Although the fatality rate of this disease is relatively low (0.03%) compared to other food-borne pathogens, *Campylobacter* spp. continues to be the leading cause of reported zoonosis gastroenteritis in EU (EFSA, 2018).

A relationship between temperature increase and human campylobacteriosis has been reported in different studies (Cullen, 2009; Kovats et al., 2005; Louis et al., 2005). Kovats et al. investigated the impact of climate change on *Campylobacter* infections in different continents and concluded that there was a pronounced seasonality of campylobacteriosis both in Europe and Canada, with a peak in recorded cases between April and May and June and July, respectively (Kovats et al., 2005).

A few years later, Cullen predicted that climate change could result in a 3% increase in incidence of campylobacteriosis infections (Cullen, 2009). On the contrary, a study investigating the combined impact of multiple climatic factors, including temperature, on the incidence of campylobacter infections in South Korea did not identify any strong correlation between climate factors and *Campylobacter* transmission (Park, Park, & Bahk, 2018).

In these studies, the association between the increased ambient temperature and the increased likelihood of campylobacteriosis was neither consistent nor strong as compared to other food-borne pathogens such as *Salmonella* spp. This could partially be explained by differences in methodology and collected data and/or by the regional differences in weather conditions. In the same vein, differences among previous studies may arise due to different study areas. Therefore, it could be assumed that climate change might not have the same impact on campylobacteriosis infections among different areas. However, other studies proposed that temperature can indirectly influence campylobacteriosis through the seasonality of fly transmission (Ekdahl, Normann, & Andersson, 2005; Nichols, 2005) and primary drivers of this disease remains to be investigated (Djennad et al., 2019).

5.2.2. Salmonellosis

Salmonellosis is the second most commonly reported food-borne disease, caused by *Salmonella* spp. In 2017, European Union reported 94.530 confirmed cases of salmonellosis (EFSA, 2018). The seasonality of salmonellosis has been observed in EU between 2012 and 2016, with a peak in recorded salmonellosis during summer months (EFSA, 2018).

The observed seasonality of salmonellosis could be explained by the correlation between the environmental temperature and *Salmonella* spp. The association between increased ambient temperature and elevated cases of salmonellosis is strong and the biological mechanism behind this phenomenon have been well-investigated (Lake, 2017). Some examples of reporting a potential correlation between salmonellosis cases and climatic factors can be found in Europe (Kovats et al., 2004; I. R.; Lake et al., 2009) and US (Jiang et al., 2015).

5.2.3. Vibriosis

Vibrio spp. is a natural inhabitant of the marine environment. Some species of *Vibrio* are pathogenic to humans and can be transmitted through consumption of contaminated shellfish, usually raw oysters, or through contaminated water. According to Centers of Disease Control and Prevention (CDC), vibriosis causes approximately 80,000 illnesses and 100 deaths in United States each year (CDC, 2020). Among the different *Vibrio* species, *Vibrio parahaemolyticus* and *Vibrio vulnificus* are the ones usually associated with vibriosis cases occurring due to consumption of seafood, while *Vibrio cholerae* is the species leading to cholera illness through contaminated water.

Although *Vibrio* spp., excluding *V. cholerae*, is considered as a moderate risk to human health, a strong link to climate change has been demonstrated (Lindgren, Andersson, Suk, Sudre, & Semenza, 2012). Several climatic factors such as sea surface temperature, precipitation, flooding and salinity may change the proliferation of this species (Tirado et al., 2010). Nevertheless, genetic factors also play an important role in the presence of *Vibrio* spp. (Marques et al., 2010). A study investigated the emergence of *V. parahaemolyticus* in Alaska concluded that ocean warming is a key factor but also highlighted the fact that the involved strain might be more virulent than other strains isolated elsewhere (González-Escalona et al., 2008).

5.3. Climatic-driven emerging risks

Climate change was identified as a potential driver of re-emerging new risks and as a factor that may increase the exposure or the susceptibility to known hazards (EFSA, 2020). Precipitation and flooding play an important role in waterborne diseases, since waterborne outbreaks have reported to typically become increased after heavy precipitation events (Guzman Herrador et al., 2016). Heavy precipitations lead to waterborne outbreaks either through floods which may damage critical water supplies or through storm runoff that may mobilise and transport pathogens (Semenza, 2020).

While precipitation events have increased both in number and extent, especially after long periods of drought driven by anthropogenic factors, increase in pathogenic and parasitic loads in water should be expected. Although parasites, such as *Cryptosporidium*, are not a direct threat to human life, they may pose a risk since they are resistant to chlorination and during heavy precipitation events might be easily transmitted from animals to human through water.

Increased temperature has been found to affect thawing permafrost and the snow-freeze melt process. It can be expected that pathogens, including bacteria and viruses, that preserved in frozen ground for many centuries may revive and release in the environment (EFSA, 2020). Likewise, metal-interacting bacteria, including pathogenic bacteria such as *Pseudomonas* that are present in snow and frost may also be released in the environment and pose risk to human health through consumption of fishery and aquaculture products (EFSA, 2020).

Nevertheless, it is important to highlight the fact that high level of uncertainty accompanied the complex interactions between climate change, food matrixes, food contamination and food-borne diseases. Therefore, prioritised monitoring and epidemiological surveillance should be in place in order to identify emerging risks for human health.

6. Impact of climate change on food spoilage

Most studies on climate change impacts deal with the repercussions on the primary food production and the consequences on food security, food safety and nutrition, by mainly addressing the question of the effects of pathogens on human health. On the contrary, only limited scientific evidence is available regarding the impact of climate change on food spoilage.

Food spoilage may lead to significant financial losses for the food industry while contributes greatly to global food waste which is estimated to be about one-third of all food produced with distribution and consumption stages to contribute almost 35% of the total food waste (FAO, 2011). Furthermore, food spoilage is closely related to food security. Even though food security is out of the scope of this review, it should be highlighted that food security, safety and quality are three elements highly interactive with one another. The four dimensions that constitute food security, namely availability, access, utilisation and stability should be ensured in order to achieve food security. Given the fact that for many regions, including the Mediterranean and central Europe, food availability is estimated to be reduced following a 2 °C temperature increase (Hoegh-Guldberg et al., 2019), it is now more crucial than ever to guarantee food security. Achieving food security in a changing world is impossible without considering food spoilage which directly affects utilisation and stability of the available food products.

Food spoilage is defined as the process that renders a food unacceptable to the consumer. Microbiological spoilage is by far the most common cause of food spoilage (Gram et al., 2002). Growth of the "Specific Spoilage Organisms (SSO)" to a certain level results to spoilage due to a quality defect such as off-flavour, off-odour, visual microbial growth (e.g. slime, mycelia), textural change (e.g. coagulation) etc, which subsequently lead to the sensory rejection of the product by the consumer. (Gram et al., 2002; Koutsoumanis & Nychas, 2000; Koutsoumanis, Stamatiou, Skandamis, & Nychas, 2006). As in the case of pathogenic bacteria, climatic factors such as temperature, humidity, heavy precipitations events are expected to affect spoilage microorganisms and increase the risk of spoilage. Among the several raw materials and food products bulk dried foods such as, cereal grains and non-refrigerated processed foods are considered to present a high susceptibility to climate change in relation to spoilage since temperature, humidity and precipitation could change their intrinsic and/or extrinsic factors which affect the growth of spoilage bacteria.

6.1. Impact of global warming on the spoilage risk of non-refrigerated processed food products

Based on the probabilistic forecast of CO_2 emissions and temperature change developed by IPCC, the likely increase of global temperature is predicted to be between 2 and 4.9 °C, with a mean of 3.2 °C (IPCC, 2014). This projected increase in temperature due to climate change, could affect the microbiological stability of non-refrigerated food products by increasing the growth potential of spoilage microorganisms during transportation and storage (on retail and domestic level), and subsequently lead to a higher risk of spoilage with considerable losses of economical and physical resources.

Non-refrigerated processed food products are microbiologically stable foods which will not spoil or cause disease when stored at ambient temperature. They include foods with a significant share in the food market such as canned foods, products processed with Ultra High Temperature (i.e UHT milk), pasteurized high acid foods (fruit and vegetable juices), etc. Most of them are contaminated with spores of spoilage bacteria which are extremely heat resistant and can survive a thermal process designed to control pathogens. These thermostable spoilers include species of the *Bacillus, Geobacillus, Alicyclobacillus, Anoxybacillus, Brevibacillus, Paenibacillus* and *Moorella* genus (André, Zuber, & Remize, 2013; McClure, 2006). The microbiological stability of non-refrigerated food products is based on the fact that the survivors of the thermal process are thermophilic and require a certain storage time at high temperatures in order to grow to spoilage levels which are currently very rare under normal distribution and storage conditions.

In the present study we provide two examples on the potential impact of climate change to the risk of spoilage of non-refrigerated food products related to pasteurized fruit drinks and evaporated milk. In both examples predictive growth models of thermophilic spoilage bacteria are combined with temperature data extracted form available databases (www.weatherground.com) to evaluate the effect of current distribution and storage conditions on the risk of spoilage compared to simulated global warming scenarios.

The first example refers to heat processed fruit drinks which are considered as microbiologically stable food products mainly due to their low pH (<4.0). However, a large spoilage incident of apple juice in Germany in the early 80's, reveal *Alicyclobacillus acidoterrestris* as the causative agent (Cerny, Hennlich, & Poralla, 1984). This spore-forming bacterium has been recognized as a major spoiler in the fruit industry (Huang, Yuan, Guo, Gekas, & Yue, 2015), due to its heat resistant spores and their ability to germinate and outgrow in acidic environments. Hence, spores that have survived heat treatment can germinate and outgrow. After multiplication, the metabolically active cells reach critical cell concentrations at which spoilage taint compounds can be produced leading to organoleptic rejection of the products. In the case of fruit drinks, *A. acidoterrestris* produces guaiacol which causes the undesirable effect of phenolic, medicinal, antiseptic off-flavours (Huang et al., 2015) when its concentration reaches about 10^4 CFU/mL (Bahçeci, Gökmen, & Acar, 2005).

We assessed the potential effect of climate change on the spoilage risk of heat processed fruit drinks by combining a predictive growth model of *Alicyclobacillus acidoterrestris* developed by Kakagianni and colleagues (Kakagianni et al., 2018) with hourly temperature data obtained from an online database (www.weatherground.com) for Dublin (Ireland) during 2019 and a simulated scenario of global warming. More specifically, the growth behaviour of *A. acidoterrestris* ATCC 49025 in a fruit drink with a pH of 3.52, was predicted for an hourly temperature profile of 2019 and for a scenario of 3 °C average temperature increase. The results of the assessment (Fig. 2) showed that current temperature conditions did not allow growth of *A. acidoterrestris* in a fruit drink during distribution and storage for a year in Dublin supply chain. However, in case of 3 °C temperature increase, an increase of 5.7 log CFU/ml was predicted by the model which can lead to quality defects such as the production of off-odours in fruit drinks occur due to production of guaiacol, (Kakagianni et al., 2018).

In another similar example in evaporated milk a predictive growth model of *Geobacillus stearothermophilus* developed by Kakagianni and colleagues (Kakagianni, Gougouli, & Koutsoumanis, 2016) was combined with the observed temperature data of Albania for 2019, obtained by the same online database. The latter thermophilic spore-forming bacterium constitutes the most important spoilage problem for the food industry in relation to thermally processed shelf stable milk and other food products. Among the major factors explaining its persistence in industrial environment, the high prevalence and the high level of spore loads in the raw materials, along with the extreme heat resistance of *Geobacillus* spores have been identified as the most crucial factors (André et al., 2013). As soon as the spores are exposed to favourable temperatures (>33 °C) they transit from an inactive form to active cells after an irreversible cascade of steps (Kakagianni et al., 2016). The growth of metabolic active cells to critical levels (close to 10^7 CFU/g) results in acidification and further coagulation which is a persistent quality problem for the dairy industry (Burgess, Lindsay, & Flint, 2010; Kakagianni et al., 2016; Rigaux, André, Albert, & Carlin, 2014).

As it is illustrated in Fig. 3, current temperature conditions did not allow growth of *G. stearothermophilus* in UHT milk, which is stored and distributed for a year in Albanian supply chain. Nevertheless, in the

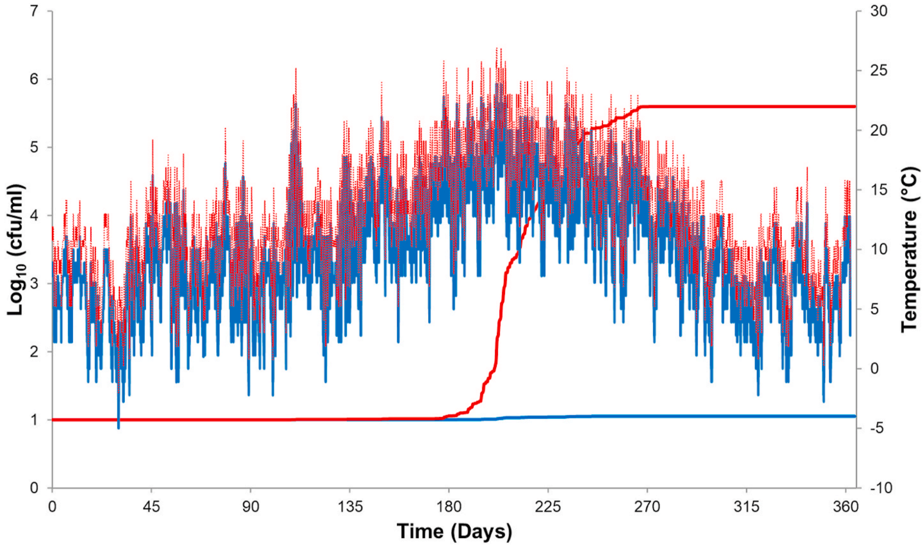

Fig. 2. Predicted growth of *Alicyclobacillus acidoterrestris* ATCC 49025 in fruit drink (pH 3.52) with a shelf-life of one year in the supply chain of Ireland for 2019. Growth prediction is based on the combination of the predictive growth model and the observed daily temperature data during 2019 (—) and a scenario of 3 °C (—) temperature increase, in Dublin, Ireland.

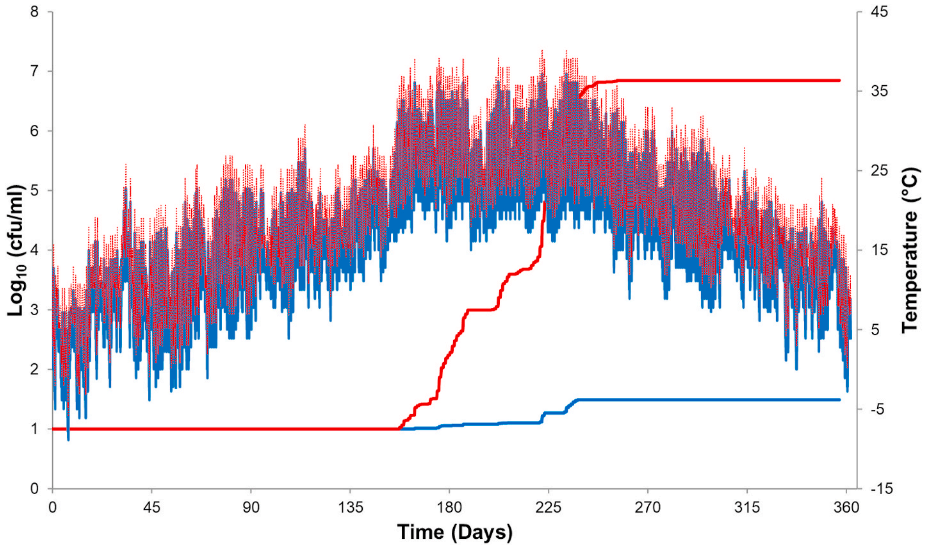

Fig. 3. Predicted growth of *Geobacillus stearothermophilus* ATCC 7953 in UHT milk with a shelf-life of one year in the supply chain of Albania for 2019. Growth prediction is based on the combination of the predictive growth model and the observed daily temperature data during 2019 (—) and a scenario of 3 °C (—) temperature increase, in Tirana, Albania.

simulation of 3 °C temperature increase, spores of *G. stearothermophilus* were predicted to be able to germinate and reach almost 10^7 CFU/ml. Generally, presence of *G. stearothermophilus* in UHT lead to quality default due to acid coagulation. This failure is observed when *G. stearothermophilus* reaches its maximum level and pH decreases to 5.2 (Kakagianni et al., 2016). Therefore, temperature increase may allow growth of this microorganism to its spoilage level and subsequently lead to a significant increase in the risk of spoilage.

A systematic evaluation of the impact of climate change on food spoilage requires quantitative microbiological spoilage risk assessment (QMSRA) approach which takes into account uncertainty and variability that usually accompany such a complex question. However, the above simulation examples provide strong indications that the current distribution and storage conditions in many European countries are marginal in limiting the growth of spoilage thermophilic bacteria present in non-refrigerated foods and a future temperature increase due to climate change could "break" their microbiological stability. This could result in significant social-economic consequences and would require a high level of preparedness by both the food industry and policy makers.

6.2. Impact of increased precipitation events and humidity on bulk dried food and cereal grains

Beyond the above-mentioned global warming effect on food spoilage, other climatic factor, such as heavy precipitation events and humidity, should be investigated for their impact on fungal spoilage of bulk dried food and especially cereal grains. According to the predictions provided by IPCC, elevated surface humidity should be expected as a consequence of these combined climatic factors. However, relatively humidity will most probably remain at the same levels (IPCC, 2014).

As it is discussed in section 2.1, increased temperature, humidity and precipitations favour fungal growth. Fungi are known to have a moisture and temperature range in which they perform better and thus, increased temperature and precipitation events may change the range of latitudes and altitudes at which certain fungi are able to compete. In addition, post-harvest conditions can also increase the fungal growth. The stability of grains during storage is mainly influenced by the condition of the grains to be stored at the point of harvest. Therefore, climate change may alter the degree or the nature of variation of conditions and subsequently the stability of grains during storage (Tirado et al., 2010) and induce an increased risk of spoilage.

Fungal contamination of cereal grains mainly occurs due to colonisation of *Aspergillus* and *Fusarium* species. With regards to *Fusarium* spp. the most affected crop is maize, while corn is the most susceptible crop to *Aspergillus* spp. contamination. Both fungi have been found to get influenced by both temperature and water activity (a_w), with the latest to be characterised as the most significant growth factor (Samapundo et al., 2005, 2007). Thus, monitoring of humidity and temperature during storage process may significantly reduce the risk of fungal spoilage. Given the expected increase in temperature and precipitation events, it is still a matter of debate whether the existing food safety management systems are able to prevent fungal contamination during storage in the upcoming years.

Kinetics and probabilistic models for the assessment of the effect of temperature and a_w on the colonial growth of *Aspergillus flavus* have been developed (Astoreca, Vaamonde, Dalcero, Ramos, & Marín, 2012). In order to verify our previous assertion, we combined the predictive growth model of *Aspergillus flavus* BAFC4273 developed by Astoreca and colleagues with hourly temperature data obtained from an online database (www.weatherground.com) for Denmark in 2019. The obtained data were further used to assess the impact of climate change (i.e. global warming, increased precipitation events) on the fungal spoilage of corn by simulating different climate change scenarios.

Three different climate change scenarios were designed in order to assess the impact of rising temperature and elevated surface humidity independently, as well as their combined effect on growth of *Aspergillus flavus* BAFC4273 mycelium diameter in corn (Fig. 4). For simulation purposes, observed daily temperature data for Denmark in 2019 were used. In the first scenario, effect of global warming on the mycelium diameter (g) was estimated based on the observed daily temperature data and a scenario of 3 °C increase for a_w 0.80. As it is illustrated in Fig. 4, current temperature conditions are not expected to allow growth of mycelium diameter above 2 mm per year. However, under 3 °C temperature increase maximum mycelium diameter is expected to increase and reach 3.6 mm per year.

In the second scenario, effect of surface humidity on mycelium growth under the current temperature conditions was assessed. For this reason, two different a_w levels were selected; namely 0.80 and 0.81, respectively. As it was expected, increased water activity lead to the formation of approximately four-times bigger mycelium (8.06 mm). In the third scenario, maximum mycelium diameter was predicted based

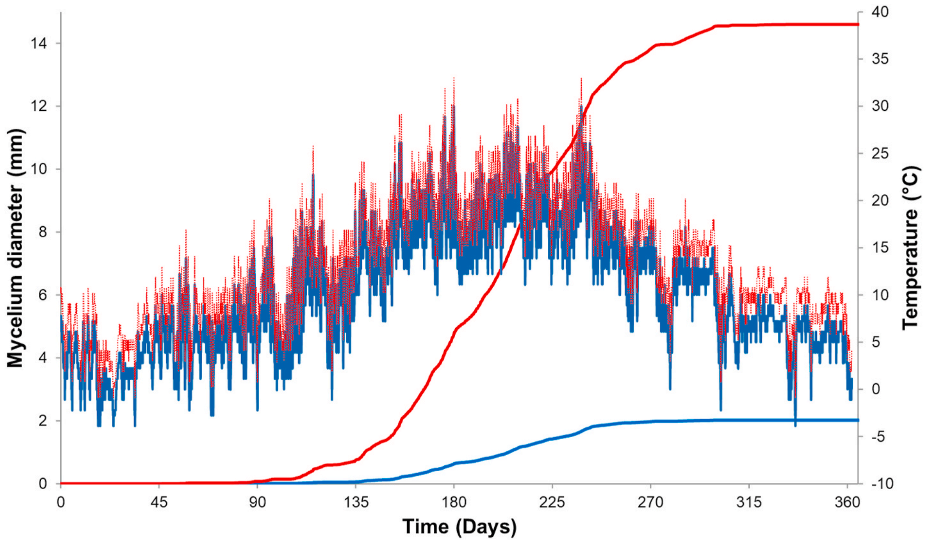

Fig. 4. Predicted growth of *Aspergillus flavus* BAFC4273 mycelium diameter in corn for different scenarios of temperature and precipitation event increase. Mycelium diameter estimation is based on the combination of the growth model and the observed daily temperature data for 2019 in Copenhagen, Denmark and a level of water activity, a_w 0.80 (—), and a scenario of 3 °C temperature increase and a level of water activity, a_w 0.81 (—), respectively.

on the combined effect of rising temperature (+3 °C) and water activity (0.81). Under this scenario, maximum mycelium diameter is expected to reach approximately 14.5 mm per year. According to the provided data, the maximum colony diameter is mainly influenced by the a_w, with higher a_w resulted to the formation of significantly bigger mycelium. Therefore, projected climate changes and especially extended precipitation events may lead to an increased risk of spoilage.

Hence, in order to minimise the risk of fungal spoilage during the foreseen climate change, combined effects of elevated temperature and surface humidity should be taken into consideration in the design of food safety management systems.

7. Conclusion

In conclusion, the climate change is unequivocal since world has already started facing its implications. Climatic factors including global warming, natural disasters, increased frequency of heavy precipitation events, extended dry periods and potentially rising sea levels are projected to alter and directly affect agriculture, fishery and livestock production in multiple ways. Subsequently, food products can be directly and indirectly affected by climate change at a worldwide level. Potential impact of climate change on food safety at various stages of the food chain have been reviewed, including mycotoxin and biotoxin contamination, environmental residuals, food- and water-borne diseases occurring from zoonosis diseases and climatic-driven emerging risks. Moreover, this review aims to raise attention to the potential impacts of climate change on food spoilage and quality of two main food categories; namely cereal grains and non-refrigerated food categories.

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