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Review

Climate Change and Emerging Food Safety Issues: A Review

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ABSTRACT

Throughout the past decades, climate change has been one of the most complex global issues. Characterized by worldwide alterations in weather patterns, along with a concomitant increase in the temperature of the Earth, climate change will undoubtedly have significant effects on food security and food safety. Climate change engenders climate variability: significant variations in weather variables and their frequency. Both climate variability and climate change are thought to threaten the safety of the food supply chain through different pathways. One such pathway is the ability to exacerbate foodborne diseases by influencing the occurrence, persistence, virulence and, in some cases, toxicity of certain groups of disease-causing microorganisms. Food safety can also be compromised by various chemical hazards, such as pesticides, mycotoxins, and heavy metals. With changes in weather patterns, such as lower rainfall, higher air temperature, and higher frequency of extreme weather events among others, this translates to emerging food safety concerns. These include the shortage of safe water for irrigation of agricultural produce, greater use of pesticides due to pest resistance, increased difficulty in achieving a well-controlled cold chain resulting in temperature abuse, or the occurrence of flash floods, which cause runoff of chemical contaminants in natural water courses. Together, these can result in foodborne infection, intoxication, antimicrobial resistance, and long-term bioaccumulation of chemicals and heavy metals in the human body. Furthermore, severe climate variability can result in extreme weather events and natural calamities, which directly or indirectly impair food safety. This review discusses the causes and impacts of climate change and variability on existing and emerging food safety risks and also considers mitigation and adaptation strategies to address the global warming and climate change problem.

HIGHLIGHTS

- Climate change may heighten the occurrence and virulence of foodborne pathogens.
- Risk of contamination of food by chemical hazards will also likely increase.
- Climate change may likely result in a rise in foodborne infection and intoxication.
- Frequent extreme weather events brought by climate change also affect food safety.
- Ensuring food safety under a changing climate requires key adaptation strategies.

Key words: Adaptation; Climate; Food hazards; Food safety; Mitigation

Climate change has literally become a hot topic and an alarming issue worldwide. From literature, climate change is defined as a long-term change in statistical properties of the climate system and is demonstrated by an unusual distribution around the recorded mean over an average period of 30 years *(20, 86)*. Climate change encompasses variations in atmospheric carbon dioxide, changes in worldwide temperatures and precipitation, which all, in turn, influence sea levels and salinity, crop yields, soil quality, nitrogen deposition, plant diversity, and crop diseases *(20)*. The principal cause of climate change is greenhouse gas (GHG) emission, and the climatic factors influenced are temperature, relative humidity, precipitation, and UV, thus resulting in climate variability *(33, 48, 86)*. According to the International Panel on Climate Changes and several authors, global climate models have projected a mean global warming ranging from 1.5 to 5.8°C and a rise in the mean global precipitation of 5 to 15% by the end of the century *(71, 79, 86)*. A significant shift in the variables can induce meteorological hazards, such as extreme weather events, with weather variables and frequency below or above the fixed mean threshold *(18),* as well as natural calamities, which are sudden localized extreme hydrological, geophysical, meteorological, or climatological events *(60)* (Fig. 1). Extreme weather events, which usually have a frequency of less than 5% will become more recurrent due to the impact of climate change *(86)*. Many extreme weather disasters, such as floods, heat waves, and winter storms have been recorded in Europe over the last two decades. Several floods have struck northern Italy, France, and Switzerland in 2000, the United Kingdom in 2007, as well as Germany and France in 2016 *(43)*. Severe heat waves occurred in the summers of 2003, 2010, and 2018 *(43)*.

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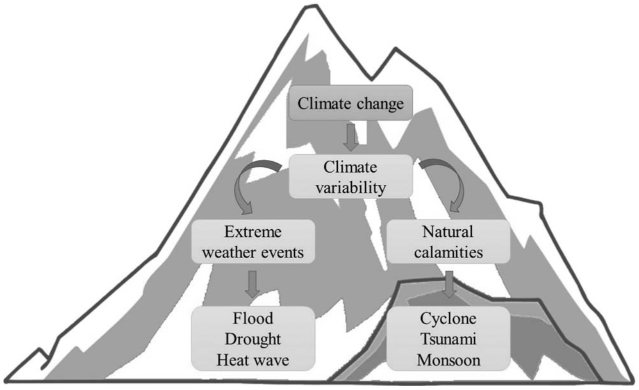


FIGURE 1. *Relationship among climate variability, the effects of climate change, and other related phenomena.*

Furthermore, winter storms were recorded in 2007 and 2010 *(43)*. Other examples include extreme snowpack in the northern Alps in 2006 and 2019, wildfires in southern and eastern Europe in 2007, 2010, and 2017, and hailstorms in Germany in 1984 and 2013 *(43)*. As for natural calamities, namely, tropical cyclones, tsunamis, and monsoons, these may be accompanied by intense rainfall, severe flooding, and high winds *(79)*. It is now acknowledged that with the progress of climate change, extreme weather events and natural calamities will become more frequent and more extreme *(43)*. However, before delving into the influence of climate change and food safety hazards, we need to first understand the physical causes and broad impacts of this phenomenon.

CLIMATE CHANGE: ITS PHYSICAL CAUSES

Because the Earth's atmosphere is made mostly of nitrogen and oxygen, the Earth's climate is influenced by the water cycle and carbon cycle. Carbon dioxide (CO_2), together with methane (CH_4), nitrous oxides (NO and N_2O), and ozone (O_3), make up the GHGs that trap heat in the Earth's atmosphere. Although individually present as small amounts, they have the biggest role in changes in climate, as the level of GHGs is directly related to atmospheric temperature. For instance, an increase in GHG level in one region in the world can alter the climate of the whole planet due to its release in the atmosphere. Eventually, an excessive rise in GHGs creates the greenhouse effect, thus giving rise to climate change *(32)*. GHGs are naturally present in the Earth's atmosphere, to maintain a proper environment for life, but their levels can change due to natural processes, as well as human activities. CO_2 is the most abundant of the GHGs with a much greater impact on temperature worldwide *(32)*. Because CO_2 and temperature are closely correlated, an increase in CO_2 implies increased warming of the Earth. Hence, the excessive release of CO_2 in the atmosphere is the root cause of global warming and, consequently, of climate change *(32)*. Because 80% of GHGs are associated with human activities, the phenomenon has been more appropriately termed as "anthropogenic climate change" *(32)*. Human activities include the altered use of land from forests to farmland or industrialization, as well as the use of manmade GHGs, such as chlorofluorocarbons and air pollution. GHGs, some of which have been trapped for millenniums in fossil fuels and biomass, are also being added to the atmosphere by humans *(32)*. Altogether, human activities greatly alter the composition of the Earth's atmosphere and bring about consequent changes in climate. However, climate models trying to replicate the current conditions of climate change have not worked by solely considering the human dimension because the underlying natural causes also have a role to play *(32)*. Having said that, human activities, especially since the Industrial Revolution, have been the main contributor in advancing the release of CO_2 in the atmosphere *(32)*.

BROAD IMPACTS OF CLIMATE CHANGE

The main result of the increased release of CO_2 in the Earth's atmosphere is global warming, thus contributing greatly to climate change. This rise in temperature has had an impact on the different components of the Earth, be it the atmosphere, the hydrosphere, the cryosphere, the geosphere, or the biosphere *(21, 32)*. Some of the main environmental impacts of climate change include warmer temperatures, alteration in the water cycle, and more severe and more frequent extreme weather events, which include heat waves, droughts, and floods *(32)*. Melting of ice caps, ocean warming and acidification, rise in sea level, increased erosion, and changes in deep ocean circulation are additional effects of warming *(32)*. Altogether, these will have a direct impact on the ecosystem food security and indirectly on food safety and human health.

Arctic, oceans, and agricultural land. Temperature patterns show that the Northern Hemisphere will undergo warming to a greater extent than the Southern Hemisphere, as it is mostly land *(32)*. Polar regions will also warm up more than the rest of the planet due to the transition of ice to liquid water *(32)*. With the continuous melting of the Arctic, animals such as polar bears and seals, may become extinct and lead to an imbalance in the food chain, as well as a threat to food security in the Arctic region. Between 2030 and 2050, it has been predicted that Australia's Great Barrier Reef will undergo annual bleaching due to increasing temperatures, ocean acidity, and higher sea level *(32)*. In fact, almost all coral reefs in tropical areas are expected to disappear by 2050 *(66)*. Eventually, the loss of coral reefs will affect not only the ecosystem but also food sources, including commercial fisheries. The impact of climate change on the ocean has already affected the volume and distribution of fisheries and marine organisms *(66)*. Several cold-water species are being reduced, and some tropical species are being redistributed *(66)*. Ocean warming and acidification can further affect the reproduction processes of some marine species, such as shellfish, which are sensitive to acidification *(66)*. Also, microorganisms, such as bacteria and phytoplankton, which are key to the marine food web will also be impacted *(66)*. Overall, the combined aquatic stress may disrupt the food chain in the marine ecosystem, leading to a reduced stock of commercial marine species in some parts of the world. Impacts of increased temperature and tropical cyclonic activity will also likely affect the capture, production, and marketing costs of marine fish *(68)*. It has been predicted that tropical areas, especially small islands that depend on fisheries for the economy and for human consumption, will suffer from poverty and ensuing health and hygiene problems *(66)*. As for agricultural food production, in mid to high latitudes that had typically cooler climates, warming in these regions is expected to cause an increase in yields of food crops. However, higher latitudes will suffer from hotter and drier conditions, with a reduced agricultural productivity, less access to clean water for irrigation, and increased plant diseases and pests *(32)*. Models have predicted that CO_2 doubling will result in losses of 10 to 50% of agricultural croplands and a decrease in the global yield of key food crops between 10 and 70% *(32)*. Furthermore, with reduced arable land and with projected increased human migration associated with climate, there are more challenges and risks associated with the successful cultivation of crops and rearing of domestic animals. As a result, food security is threatened, famine may become more common in areas, such as sub-Saharan Africa and many other regions, and food safety can be greatly impaired, putting human health at stake *(32)*.

Water cycle. The water cycle is also affected by climate change, with decreasing rain in drier areas, such as midcontinental regions, and increased rain in wetter areas, such as monsoon and tropical regions, thus greatly affecting the agricultural sector. About 1.7 billion people are already living in countries that are water stressed, and by 2025, the number will likely rise to 5 billion *(32)*. The most water-stressed countries are located in the Middle East and North Africa region, with Qatar, Israel, and Lebanon figuring among the most water-stressed countries *(81)*. Droughts will become longer and fiercer, and many marginal regions will become almost impossible to inhabit *(32)*. Coupled with heat waves, drought will contribute to losses in agricultural productivity along with shortness of a clean water supply *(32)*. With expanding water insecurity issues, there may be the increased use of contaminated irrigation water for cultivation with ensuing foodborne and waterborne disease risks. In addition, the emergence of new waterborne pathogens and parasites may perpetuate a vicious cycle of food and waterborne diseases, again threatening food security and safety. Also, diseases common to tropical regions will likely spread to temperate zones, affecting developed, as well as developing nations *(32)*. Some of the infectious diseases expected to increase are malaria, encephalitis, yellow fever, cholera, and dengue fever *(32)*.

Human migration and settlements. With climate change, more frequent extreme climatic events, such as windstorms, heat waves, heavy rainfall, droughts, and floods are predicted *(34)*. This is likely to cause resettling of people to other regions that are less prone to these risks. Moreover, over time and with changes in agricultural and industrial land use in some areas of the world, massive migrations and redistributions of people could occur *(32)*. This shift in human settlement patterns may cause overpopulation in some parts of the world *(32)*. Also, as people migrate from low-lying coastal areas to interior areas or from drought-affected farms to cities, this gives rise to more urbanization *(32)*. As the "climate-change immigrants" move to new lands, there can be an overpopulation that, in turn, brings about socioeconomic disruptions, compromised food security and safety, and negative health impacts *(32)*. This is expected to exacerbate the problem of deforestation, as there is a quest for more land and infrastructure, thus leading to further release of CO_2 in the Earth's atmosphere.

RELATIONSHIP AMONG FOOD SAFETY AND CLIMATE CHANGE, CLIMATE VARIABILITY, AND CLIMATIC FACTORS

It has been documented that climate change is an important driver of emerging risks, threatening food and feed safety, plant and animal health, and nutritional quality, as shown in Table 1 *(48)*. However, with the number of hazards and factors involved, there are large uncertainties in the relationship between climate change and food safety. Climate change is thought to have an adverse impact on humans, plants, animals, and environmental systems with the potential to exacerbate the frequency and severity of certain foodborne diseases *(78)*. According to the Fourth Report by the United Nations International Panel on Climate Change, increased temperatures, elevated CO_2 levels, changes in rainfall pattern, and extreme weathers will likely compromise food safety *(80)*. The climate change and emerging risks for food safety project, a multidisciplinary network consisting of international and intergovernmental experts involved in climate change, aims to identify emerging risks linked to climate change in relation to food safety. It came to the conclusion that climate change impacts on the occurrence, persistence, dominance *(78, 79),* and toxicity of marine and freshwater algal blooms, bacteria, fungi, viruses, parasites *(40, 86),* as well as vectors pathogenic to plants and animals *(48)*. As a result, changes in climatic factors will likely influence the (i) sources and modes of transmission, (ii) growth and survival, and (iii) ecology of pathogens in food *(78, 86)*. For instance, temperature changes may affect the reproduction period of pathogens, thereby altering distribution and growth, and in some areas, lead to the emergence of new pathogens for a specific host *(86)*. Major outcomes of climate change are the emergence of new hazards or an increased host susceptibility to existing and known hazards *(48)*.

MICROBIOLOGICAL HAZARDS AND CLIMATE CHANGE

There can be a range of hazards that can compromise the safety of food at various points along the production chain. For example, because microorganisms are ubiquitous in nature, pathogenic microorganisms coupled with climate change, can contaminate food at any stage, from farm to fork *(54),* as illustrated in Figure 2. Foodborne pathogens are mainly hazardous bacteria, viruses, or parasites that are present in food, leading to food poisoning or foodborne

TABLE 1. *Summary of major effects of climate-dependent environmental factors on the behavior of foodborne pathogens and impact on food safety*[a]

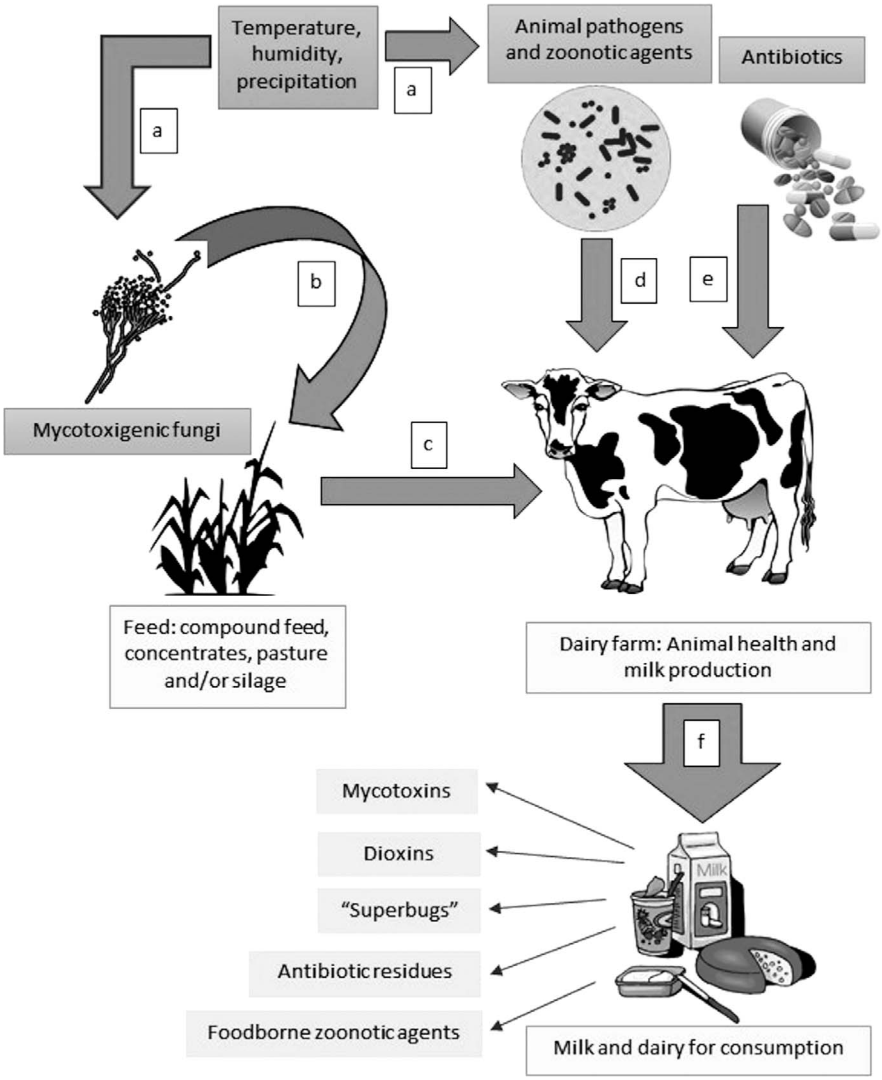
	Effect of climate on environmental factors involved in the growth, survival, and pathogenicity of foodborne pathogens
Temperature	
Increase	Increased occurrence of parasites in freshwater fish and plants *(33)* Detection of new mycotoxin-producing fungal species in maize in Europe *(56)* Increase in mastitis incidence in cows *(44)* Increase in *Salmonella* in poultry *(33)* Increased number of *Vibrio* cells in seafood *(50)*
Decrease	Increased contamination of berries by norovirus and hepatitis A *(11, 23)*
Precipitation and humidity	
Increase in precipitation	Internalization of pathogenic *E. coli* and *Salmonella* in leafy green vegetables *(29, 47)* Increased contamination of seafood by fecal indicator organisms due to water runoffs *(50)* Increased risk of splash dispersal and aerosolized *Salmonella* infecting tomatoes due to increased frequency of short period of heavy rainfall *(15)*
Decrease in precipitation and humidity	Increased mycotoxin contamination by xerophilic fungi in maize at preharvest stage *(56)*
pH and salinity	
Decrease in pH	Ocean acidification leads to increased HABs *(50)*
Decrease in salinity	Increases in bioaccumulation of toxic metals in molluscs *(86)*
Light	
Increase	Favors the growth of HABs *(50)*

[a] Adapted from Duchenne et al. *(22)*.

diseases *(72)*. According to the Centers for Disease Control and Prevention, foodborne hazards are classified by food hazard pairs, that is, food frequently associated with the hazard of interest *(72)*. Some examples of common food hazard pairs are histamine and fish, *Salmonella* and poultry, *Campylobacter* spp. and dairy products, *Vibrio* spp. and mollusks, and noroviruses and leafy green vegetables or shellfish *(72, 78)*. Contamination of food by infectious, toxicoinfectious, or toxigenic organisms can occur in various food sectors, including crop, livestock, and seafood production, and these are highly influenced by environmental determinants *(73)*. For example, heavy rainfall can cause runoffs of human sewerage in fresh watercourses, thereby contaminating water used for irrigation of crops. Weather and climate factors, in turn, affect these environmental determinants, potentially enhancing the viability, stability, reproduction, and even the transport rates of the pathogens *(73),* and altering the exposure pathways of foodborne diseases. Two highly influential climatic variables that affect the occurrence of foodborne diseases are temperature and precipitation *(73, 49)*. With the predicted rise in world temperature, this will likely increase the heat load on all systems of the cold chain *(36)*. Moreover, a 2 to 3°C rise in the temperature will likely reduce the chilled storage life by half and lead to increased food spoilage and poisoning, unless the cold chain is extended and improved *(36)*.

Foodborne diseases associated with plant-based commodities. In recent decades, foodborne disease outbreaks have been increasingly associated with the consumption of fresh produce, often as raw vegetables in salads *(2, 29, 47)*. Findings have shown that the risk of foodborne diseases is directly related to the prevalence of bacteria on leafy green vegetables. Moreover, the phenomenon of internalization of enteric pathogens, such as *Salmonella* spp. and *Escherichia coli* O157:H7, has been reported in various vegetables, including alfalfa sprouts, lettuces, tomatoes, broccoli, celery, squash, and green onion *(2, 30, 47)*. The risk of contamination of fresh produce by pathogens can be exacerbated by the consequences of climate change, such as frequent and more intense rainfall *(15),* recurring flood and drought *(14),* and temperature increase *(29, 30)*. Following heavy precipitation, levels of bacteria in the air can increase by 25- to 30-fold in agricultural fields, and splash dispersal can lead to bacterial contamination of fresh produce *(15)*. Moreover, flooding has been linked with an overflow of untreated human sewage, resulting in an increased probability of contamination of fresh produce by enteric viruses and bacteria *(78)*. Similarly, protozoan parasites, usually associated with waterborne diseases, are mostly affected by changes in precipitation pattern. Intense rainfall and flooding may also lead to increased waterborne diseases, as well as contamination of raw vegetables by protozoan parasites *(78)*. As a result, frequent flooding of cropland can facilitate the entry of human pathogens in the food chain upon consumption of contaminated raw produce *(78)*. In 2017, the U.S. Food and Drug Administration had eventually issued a warning concerning the consumption of fresh produce that had been in contact with flood water *(45)*. Drought also poses a threat to agriculture, albeit indirectly, because it leads to scarcity of clean irrigation water. In a study carried out by Ganeshan and Neetoo *(26),* tomato and bell pepper fruits were directly

FIGURE 2. *Impact of climatic factors on the safety of food at the production chain: (a) the growth and survival of micro-organims are influenced by climatic factors and the ability of the microorganisms to cause an infection or produce a toxin is dependent on the climatic factors; (b) mycotoxigenic fungi infect and colonize crops used in the feed production for animals; (c) mycotoxins produced by the mycotoxigenic fungi or dioxins present in the feed are passed to the animals via contaminated feed ingredients; (d) in the farm, animal pathogens and zoonotic agents infect the animal; (e) antibiotics are administered to the animals to treat bacterial infections; and (f) mycotoxins, dioxins, superbugs, antibiotic residues, and zoonotic agents are transferred from the animal to the food if not properly pasteurized or monitored and can also be present in processed foods (22).*



sprayed with either *E. coli* O157:H7 or *Listeria monocytogenes*. Viable bacterial cells could be recovered from the edible portion of the fruits up to 48 h postinoculation. This suggests that vegetables irrigated with contaminated water are likely to harbor human pathogens, and the latter may eventually proliferate under rising temperatures *(26)*. As such, the use of irrigation water of a poor sanitary quality may lead to the contamination of fresh produce, as exemplified by the U.S. 2008 *Salmonella* serotype Saintpaul outbreak linked to irrigated produce *(45)*. Furthermore, with increases in temperature, the transmission cycle and geographical distribution of foodborne trematodes, which are transmitted via raw or undercooked crops, are also influenced *(78)*. According to Tirado et al. *(78),* an increase in temperature may also result in accelerated disease transmission, as well as the occurrence of outbreaks in new locations. Climate change has also been found to increase the biotic stress of plants, thus making it more conducive for plant diseases *(47)*. As a result, diseased or susceptible food crops are weakened and become more prone to contamination by human pathogens, which in turn compromise food safety *(28, 78)*. Indeed, previous research has suggested that bacterial plant pathogens can enhance infiltration or internalization of human pathogens in the roots, leaves, and fruits of food crops *(19)*.

Zoonotic foodborne diseases. Climate change can also increase the risk of zoonotic foodborne diseases both directly or indirectly. As climate change affects the living conditions of livestock animals, this makes them more susceptible to microbial diseases, thus acting as major reservoirs of diseases. Moreover, an increased population of animal pests act as vectors for these zoonoses. As far as seafood safety is concerned, changes in air and sea temperature, precipitation patterns, ocean acidity, and salinity can also have an effect on the viability and disease-causing potential of human pathogens present in seawater and seafood. All these different food contamination pathways are influenced by climate change, thus posing a threat to the safety of different food commodities.

Foodborne diseases associated with poultry. A highly persistent zoonotic pathogen in poultry is *Salmonella* and is the leading cause of acute gastroenteritis worldwide *(38)*. According to Herrera et al. *(33),* past research has documented that *Salmonella* infections are directly proportional to temperature. In several European countries, salmonellosis has been found to increase by 5 to 10% for each 1°C increase in weekly temperature, for temperatures above 5°C. *(78, 86)*. Climate change–related warming is projected to favor the colonization and growth of *Salmonella* in broiler flocks *(38)*. Without proper surveillance, monitoring, and disinfection, long periods of high temperature can cause an increase in the number of *Salmonella* cells in the broiler flock. Consequently, the bacterium can be passed on in the food chain. Moreover, *Campylobacter,* also a pathogenic bacterium in poultry, is influenced by temperature. From 1999 to 2010 in Israel, an increase of 1°C above the threshold temperature of 27°C resulted in an increase of 16.1% of *Campylobacter jejuni* infections and 18.8% of *Campylobacter coli* in all age groups *(24)*. The density of common houseflies (*Musca domestica*), which may act as a vector of *Campylobacter,* is highest at mean temperatures of 20 to 25°C, and the flies are most active at low humidity *(84)*. In broiler flocks, these flies feed on litter and lay eggs, which in turn hatch within a few hours to again produce more flies *(84)*. Milder winters will increase the survivability of a range of *Campylobacter* vectors, including flies, resulting in a projected increase in campylobacteriosis *(24)*. With climate change and climatic variability, a 3% increase in the incidence of campylobacteriosis, including vectorborne campylobacteriosis, has been predicted for the coming decades *(78)*.

Foodborne diseases associated with seafood. Approximately 8% of the world's population rely on seafood as a source of food and income *(12, 41, 50)*. Bacteria, particularly *Vibrio* spp., are the main pathogenic organisms associated with seafood, and the occurrence, frequency, and severity are greatly affected by rises in temperature *(50)*. The main effects of climatic changes associated with seafood contamination are temperature increase in the upper ocean, an accelerated water cycle, ocean acidification, increased stratification, and changes in the degree of weather disturbances and rainfall patterns *(41, 50)*. In Mauritius, a tropical island, two studies investigated the effect of climate on the prevalence of *Vibrio* species in finfish and oyster respectively. Pohoroo and Ranghoo-Sanmukhiya *(64)* demonstrated a statistically higher prevalence of *Vibrio* spp., namely, *Vibrio alginolyticus, Vibrio cholerae,* and *Vibrio parahaemolyticus,* in finfish in summer compared with winter seasons. Reega et al. *(69)* demonstrated a higher *Vibrio* density in oysters in summer compared with winter. Other emerging factors that impact *Vibrio*-associated infections include drought conditions, dust emissions, and wind direction *(24)*. Aeroplanktonic adult flies (chironomids) are known to be airborne vectors of *V. cholerae,* and with wind, the bacterial disease is disseminated through the spread of the vector. Three cholera outbreaks were recorded in Africa and on the Indian subcontinent due to the spread of *V. cholerae* via aeroplanktonic adult flies *(24)*. In Alaska, warmer water increased the number of *V. parahaemolyticus* and resulted in outbreaks with more than 400 confirmed cases in summer 2004 *(24, 50)*. Soft turtles and marine fishes are colonized by *V. cholerae,* and climate change not only impacts the population density of the bacterium but also bring shifts in the habitats and distribution of those marine organisms, thus leading to more outbreaks in several countries, especially in those where such food is consumed raw or half cooked *(24)*.

CHEMICAL HAZARDS AND CLIMATE CHANGE

Mycotoxigenic fungi and mycotoxins. Mycotoxins are secondary metabolites produced by filamentous fungi belonging mainly to the genera *Aspergillus, Fusarium, Penicillium,* and *Alternaria (7, 59)*. The most toxic mycotoxins are aflatoxins, zearalenone, trichothecenes, fumonisins, and ochratoxins, as they have carcinogenic and immunosuppressive properties, affecting both humans and animals *(1, 59)*. Mycotoxigenic fungi can infect various staple crops *(62),* such as corn, rice, maize, as well as nuts, coffee, grains, dried fruits, spices, feed crops, fruits, and vegetables *(1, 4, 7),* and these can, in turn, produce mycotoxins that affect safety. For instance, there is increased concern about fungal diseases caused by *Fusarium* and *Aspergillus* spp. in staple crops, as they not only cause yield loss, but they are also mycotoxin producers that enter the food chain *(6)*. Mycotoxin contamination of food is thought to be exacerbated by the effects of climate change *(54, 63)*. The main climatic factors involved in the occurrence and prevalence of mycotoxigenic fungi are temperature, humidity, and precipitation *(62)*. Moreover, a slightly elevated CO_2 level has been found to have an impact, as well when interacting with temperature and water availability *(62)*. Some secondary factors affecting mycotoxin contamination of crops include the displacement of existing fungal species by virulent fungi, pest attacks, the effectiveness of fungicides and pesticides, and shift in the geographical distribution of insects *(62)*.

Cereals. Cereals (such as wheat, rice, and maize) constitute approximately 56 and 44% of global human and animal consumption, respectively *(6),* and are the most severely affected by pathogenic and mycotoxigenic fungi *(51, 58)*. According to the European Food Safety Authority's Emerging Risks Unit, mycotoxin contamination in maize due to climate change is a potential emerging hazard, with a risk of aflatoxin contamination expected to increase *(79)*. Typically, mycotoxin increases with relative humidity above 75% and when there is a decline in temperature in the range below 12°C or above 32°C *(62)*. However, some more virulent mycotoxigenic fungi are able to thrive in adverse conditions. The main aflatoxin producers, *Aspergillus flavus* and *Aspergillus parasiticus,* are xerophilic in nature, enabling them to thrive under higher temperatures and lower rainfall. This has been exemplified by the case in northern Italy in 2003, whereby under hot and dry spells, *A. flavus* was actively able to colonize maize by outcompeting the formerly predominant *Fusarium* spp. *(62)*. A study was carried out by Battilani et al. *(8)* on the possible emergence of aflatoxin B_1 in cereals in Europe due to climate change. It has been projected that there will be an increased risk of aflatoxin contamination in the four main maize-producing

TABLE 2. *Toxigenic* Aspergillus *species that affect the different types of nuts*[a]

Nuts	Mycotoxigenic *Aspergillus* species	Reference(s)
Peanuts	*A. flavus* *A. parasiticus* *A. niger* *A. nomius* *A. pseudotamarii* *A. bombycis* *A. minisclerotigenes* *A. arachidicola*	*76, 77*
Tree nuts (almonds, pistachios, walnuts, hazelnuts)	*A. flavus* *A. carbonarius* *A. niger* *A. ochraceus* *A. nidulans* *A. tamarii* *A. fumigatus* *A. melleus*	*10, 77*
Brazil nuts	*A. flavus* *A. parasiticus* *A. nomius* *A. arachidicola* *A. bombysis* *A. pseudonomius* *A. pseudotamarii*	*53, 77*

[a] Adapted from Taniwaki et al. *(77)*.

countries, namely France, Hungary, Romania, and northeast Italy due to an increased temperature *(8, 58)*. A number of *Penicillium* species are also xerotolerant or xerophilic, that is, they are able to colonize food products with a reduced water activity, which usually is an environmental stress for other microorganisms. As for *Fusarium* spp., they are not xerophiles but usually colonize crops at the preharvest stage and induce mycotoxin production at the postharvest stage under temperature (10 to 15°C and >30°C) and water (0.90 to 0.93 water activity) stress *(52)*. This property enables them to colonize and infect many staple crops, such as cereals, nuts, fruits, and vegetables and hence produce mycotoxin in the edible parts of the crops. Fumonisin, a mycotoxin produced by certain *Fusarium* species, occurs under drought stress, and its presence was evident in maize during the dry season in southern and eastern Africa *(62)*. Under high temperatures, the growth of the fumonisin producer *Fusarium verticillioides* is favored, thus causing it to dominate other maize-borne *Fusarium* species. The most common fungal species associated with *Fusarium* head blight in cereals was *F. culmorum* until the dawning of 2000, when *Fusarium graminearum* turned out to be more abundant on wheat *(58)*. It has been predicted that by 2050, the north European climate will become more humid, thus forecasting a shift in the *Fusarium* flora in cereal grains with *F. graminearum* becoming the dominant one *(58)*.

Nuts. The three fungal genera of importance involved in food spoilage and production of mycotoxins in nuts are *Aspergillus, Fusarium,* and *Penicillium (77)*. Several nuts, such as peanuts *(76),* tree, and Brazil nuts, are often susceptible to contamination by mycotoxins produced by toxigenic *Aspergillus* (Table 2). Drought is favorable for infection of the plant, mainly by *A. flavus, A. parasiticus,* and *Aspergillus nomius,* and facilitates production of aflatoxin at the preharvest stage *(77)*. At the postharvest stage, nuts can be contaminated by ochratoxin A produced by the toxigenic fungi *Aspergillus ochraceus, Aspergillus carbonarius,* and *Aspergillus niger (77)*. Regarding peanuts, they are mainly affected by *A. flavus* and *A. parasiticus,* resulting in aflatoxin contamination *(77)*. The level of aflatoxin produced in peanuts at the preharvest stage is greatly affected by spells of droughts. On the other hand, tree nuts, such as almonds, pistachios, walnuts, and Brazil nuts, are more susceptible to *A. flavus* at the postharvest stage and become contaminated with aflatoxins *(77)*. Brazil nuts, harvested on the ground, are also more prone to infection with *A. flavus,* producer of aflatoxin, when exposed to humid conditions *(77)*.

HAB and phycotoxins. Harmful algal bloom (HAB) is the rapid spread of naturally occurring microalgal cells or macroalgae to a bulk number that harms the environment. A number of marine microalgae that are responsible for HABs are known to elaborate natural toxins, known as phycotoxins *(65)*. Prokaryotic microalgae, such as cyanobacteria produce cyanotoxins, while dinoflagellates and diatoms, which are eukaryotic, produce marine biotoxins, also known as marine algal toxins. Several phycotoxins are neurotoxic and threaten human health and food safety *(65)*. For instance, cyanotoxins can contaminate freshwater reservoirs and drinking water, thus posing a direct threat to human health *(17)*. A study carried out by Ballah et al. *(5)* at an impounding reservoir of Mauritius noted the presence of cyanotoxin-producing microalga *Oscillatoria* and further observed that its population density increased during the "winter-to-summer" transition month of October. As for marine biotoxins, they bioaccumulate in various tissues of aquatic organisms, such as bivalve molluscs and fish, and enter the food chain upon consumption *(65)*. For example, eating seafood contaminated by saxitoxins produced by the algae *Alexandrium* can cause paralytic shellfish poisoning *(25)*. Climate change pressures are believed to have an impact on marine planktonic systems globally, and it is projected that the frequency and severity of HABs may increase *(82)*. Specific climatic factors involved in HAB occurrence and prevalence are temperature, stratification, light, ocean acidification, precipitation, and wind *(82)*. It is, thus, projected that under a changing climatic scenario, those factors will affect the current spatial and temporal distribution of HAB species. Spatially, the geographic domains of HAB species may expand, contract, or shift latitudinally *(82)*. Temporally, there may be a shift in seasons due to an increase in atmospheric and water temperature that will likely prolong summertime conditions, causing growth to contract or expand *(82)*. Temperature plays a major role in the physiological processes of phytoplankton at different growth stages and bloom development and is expected to change with climate change. However, depending on a range of factors, some coastal regions may be more affected by global warming than others. In subtropical or tropical waters, the growth of HABs may increase if temperature exceeds the optimum growth temperature *(82)*. The relationship between climate change and outbreaks of marine HABs is exemplified by the case of ciguatera fish poisoning in the tropical Pacific that was observed to increase during the El Niño period *(50)*. Consumption of seafood caught from waters where there is the occurrence of HAB thus creates a pathway for these toxins to enter the food chain.

Antimicrobials and antimicrobial resistance. Antimicrobial resistance is another emerging issue of global concern. The overuse of antibiotics in terrestrial livestock production, aquaculture, and crop production has led to an increase in pathogens that are resistant to certain antimicrobials. Approximately 73% of antimicrobial use is intended for meat production, thus giving rise to antimicrobial-resistant pathogenic microorganisms in food-producing animals *(24)*. In 2010, the global consumption of antimicrobials in livestock was 63,151 t, and this amount is projected to increase by 67% by 2030 *(24)*. Major foodborne and waterborne pathogens, namely, *V. cholerae, Campylobacter* spp., *L. monocytogenes, Salmonella* spp., *E. coli,* and *Arcobacter* spp., are increasingly showing resistance to clinically important antibiotics *(24)*. In addition to bacteria exhibiting resistance to antibiotics, there is increasing evidence of fungi acquiring resistance to antifungal drugs. With warmer temperatures brought by climate change, this will likely result in a rise in the prevalence of microbial infections, thereby increasing resistance globally. The Food and Agriculture Organization, in fact, reported that some countries have experienced a rise in the prevalence of antimicrobial resistance with an increase of average ambient temperature *(24)*. Moreover, the pathogenic fungus *Candida auris* adapted to climate change–induced warmer temperatures and replicated at 37°C *(13)*. It has been posited that warmer temperatures may facilitate horizontal transfer of resistance genes. This has been confirmed by Johnsen and Kroer *(39)* who previously reported an increase in plasmid-mediated transfer of genes between *E. coli* and *Pseudomonas putida* in response to a rise in temperature.

Use of antibiotics for food crop production. Changes in temperature and other environmental factors bring along changes and increase in geographic ranges of pests and pathogens *(78)*. This naturally implies an increase in disease burden, as well as use of antimicrobials, thus exacerbating the problem related to antimicrobial resistance. In Florida in the United States, citrus fruits suffer from a bacterial infection named "citrus greening disease" transmitted by the Asian citrus psyllid (*Diaphorina citri*) that originated from China *(24)*. To control the disease, the antibiotics streptomycin and oxytetracycline, usually used to treat human diseases, are being used in agriculture, and this use is expected to rise. Hence, this will likely result in higher amount of drug residues in plant-based commodities entering the food chain. Another example is the use of contaminated water in plant irrigation. Fresh vegetables and crops sprayed with contaminated water containing antibiotic-resistant bacteria not only act as vehicles for foodborne pathogens but also as carriers of antimicrobial residues *(78)*. Nonpathogenic foodborne microorganisms, such as *Enterobacter cloacae,* can also transfer mobile genetic elements that contain antibiotic resistance genes *(31)*. During floods, fresh produce can get contaminated with *Enterobacter cloacae* originating from untreated human sewage or during splash dispersal. Consumption of such contaminated produce can lead to foodborne illnesses, with ensuing risks of ingestion of antibiotic-resistant bacteria *(24)*. For instance, Ghaly et al. *(31)* reported that *Enterobacter cloacae* found on baby spinach leaves has the potential to transfer resistance genes to the microbiome of the human digestive tract upon ingestion *(31)*.

Use of antibiotics in livestock production. Mastitis is a common disease in dairy cattle, and it affects the mammary tissue. Mastitis caused by methicillin-resistant *Staphylococcus aureus* can lead to the transfer of antibiotic-resistant pathogen into milk, and thereafter to humans upon consumption, if not properly pasteurized *(44)*. Moreover, cows treated with antibiotics can transfer antibiotic residues into the milk, and traces of which may favor the development of "superbugs" and increase the incidence of antibiotic resistance in humans *(44)*. With the effects of global warming, dairy cattle may become more susceptible to infection by *Streptococcus agalactiae* and *Streptococcus dysgalactiae* and to increased thermal stress, affecting the milk quality and quantity, respectively *(80)*.

Fungicides and pesticides. An estimated 20 to 40% of global crop production is lost to pests, and according to the Food and Agriculture Organization Corporate Statistical Database, approximately 4.2 million t of pesticide active ingredients were used in the world's croplands in 2017 *(24)*. Over the decades, the overuse and misuse of pesticides, especially the slowly degrading ones, have had a serious impact on the environment and on water quality with toxic effects on human and animal health *(20, 24)*. Pesticides are in the human diet in the form of residues on crops that have been treated or through livestock, fish that have bioaccumulated the chemicals from their feed or water bodies, or through contaminated drinking water. Because climate change is expected to change the geographical distribution, life cycle, and population of agricultural pests and pathogens, it is predicted that there will be an increase in pesticide and fungicide use, doses, and frequency of application *(20)*. Higher temperatures favor a rapid population increase of plant pests, insects, and pathogens. For instance, in viticulture, warmer temperatures and humidity encourage fungal growth and infections, such as downy mildew (*Plasmopara viticola*) and powdery mildew (*Eysiphe necatrix*) on grapes *(16)*. As a result, there has been more aggressive pesticide use in areas with warmer temperatures. Lehmann et al. *(46)* reviewed the effects of global warming on 31 economically important phytophagous insect pests on the basis of four response categories, namely, range expansion, life story, population dynamics, and trophic interactions. Results demonstrated that 41% of the insect species are expected to increase pest damage, 4% will have a reduced effect, and 55% had mixed responses *(46)*. This suggests that although insect, pest, and pathogen populations may increase, the severity of a given insect pest may either increase or decrease with temperature increase. When combined with rising CO_2 levels and direct sunlight exposure, elevated temperatures can cause dilution and increased volatilization of pesticides and fungicides in plants, lowering the concentration, and thereby reducing their efficiency against pest and pathogens *(20)*. To keep insect damage and fungal infection in storage areas at a minimum under rising temperature and humidity, this likely calls for an increased use of pesticides and fungicides. In scenarios of intense rainfall, herbicides may not only leach into groundwater or runoff and be in water bodies, they may also become too diluted to exert any effects *(61)*. With changing patterns in precipitation and humidity, there will be increased use of fungicides and pesticides to compensate for loss through leaching *(20)*. Moreover, with global warming, crop pests and pathogens have been moving toward the pole at a rate of 2.7 (±0.8) km per year since 1960 *(24)*. With such a dramatic change in geographical distribution, it is very likely that agricultural land will experience an intensification in pesticide use, compounding the food safety risks.

Heavy metals. Heavy metals are metallic elements with a density much higher than that of water and metal pollution is known to have negative effects on the marine ecosystem and human health *(37)*. The heavy metals that are major toxicants even at low levels of exposure are lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As). Heavy metals bioconcentrate at each trophic level of the seafood chain. In a study by Bawuro et al. *(9),* zinc (Zn), Pb, Cd, and copper (Cu) were detected at a relatively low level in the flesh of fish; Zn, Cu, and Pb were accumulated in the liver, while Cd was highest in the gills. During regular consumption of fishes and seafood, heavy metals enter the human body and may accumulate in specific organs such as the kidney and liver *(37, 57)*. Factors of climate change that affect the fate of heavy metals are alterations in precipitation and temperature. More intense and more frequent rainfall patterns are predicted to enhance the runoff of heavy metals from soil and increase their leaching into water systems *(83)*. Another issue is the absorption of heavy metals by crops, which upon consumption eventually enter the food chain. Zhang et al. *(87)* reported a high contamination of heavy metals in 10.2% of arable land in China, and this affected nearly 14% of its grain production. Rice is a major crop that takes up and bioaccumulates the heavy metal As from soil *(24)*. As not only accumulates in the rice plant but in the grain consumed as well. Because it is a crop consumed in several developing countries, bioaccumulation of As in rice poses a threat to the health of millions of people. Also, a study in Bangladesh showed that the uptake of As by plants is favored under elevated soil temperatures *(58)*. This shows that the level of As in rice may double with the projected increase in soil temperatures. Elevated temperature also favors permafrost thawing, which in turn may release trapped heavy metals in water bodies, such as the ocean *(24)*. In addition, intense rainfall can also cause the wash off of heavy metals into water bodies, and the risk of subsequent absorption by marine species should not be ignored *(24)*.

EXTREME WEATHER EVENTS

Extreme weather events are unusual extreme meteorological conditions, with the climatic factor having a maximum and minimum value above and below the fixed mean thresholds and with frequencies above or below specified percentile levels *(18)*. Extreme weather events are related to human-induced climate change and is the result of increased frequency and intensity of daily temperature extremes and fluctuations of daily precipitation extremes *(35, 75)*. Climate change will likely result in shifts in the frequency and severity of extreme weather events *(34)*. These include floods, droughts, and heat waves, and all of them are characterized by an intensity above the frequency threshold or are simply out of the range of usual recorded mean values for the weather variables. It has been projected that by 2080, two to seven million people per year will face the effects of coastal flooding *(80)* and that crop and livestock production will be negatively affected.

Floods. Floods account for 40% of all extreme weather events that occurred worldwide 20 years ago *(14),* and climate change has a great bearing on the frequency, intensity, and duration of excessive rainfall and flooding. Flooding particularly affects agricultural lands and livestock farms *(74)* and increases the likelihood of microbial and chemical contamination of food and water *(78)*. In 1993, a flood in the United States led to an increase in waterborne diseases and runoff of agrochemicals into the Mississippi River and the Gulf of Mexico *(71),* with a concomitant increase in gastrointestinal illness cases *(71)*. Foodborne disease outbreaks of salmonellosis and cholera have also been recorded following flooding and spells of elevated prevailing air temperature *(84)*. Orozco et al. *(67)* detected the presence of *E. coli* and *Salmonella* Newport in tomatoes during and after flooding. Hence, fresh produce grown in flooded contaminated lands act as potential vehicles for the transmission of pathogenic microorganism. Castro-Ibáñez et al. *(14)* evaluated the effects of flood events on microbial contamination of leafy greens grown in floodplains. Soil and lettuce samples were found to have levels of coliforms and *E. coli* higher than 5 and 3 log CFU/g, respectively, when sampled 1 week after flooding. *Salmonella* was also detected in irrigation water and soil after flooding events. Because there is a significant correlation between the presence of pathogens and *E. coli* counts *(14),* the high levels of *E. coli* were indicative of pathogen presence. The study thus reinforces the hypothesis that flooding represents a main risk factor for the microbial contamination of leafy greens. In other cases, contamination can occur via injured crops. The accumulated water in flooded soils can favor the aggregation of minerals around the root, thus injuring the plant and making it more vulnerable to bacterial and fungal contamination *(29, 47, 71)*. Shiraz et al. *(74)* evaluated the effect of flooding on the microbial safety of strawberries in Louisiana. Three strains of *E. coli* were spiked in floodwater and used to flood strawberry plants for 4 h. *E. coli* was detected only in soil within 96 h of flooding, and 1.0 to 2.8 log CFU/g coliforms was detected in both the harvested mature strawberries and soil at 0, 48, 96, and 144 h in all treatments. In addition to fresh produce, farmed molluscan shellfish are also susceptible to contamination by enteric bacteria and viruses during flooding due to accumulation and diffuse discharges of human sewage *(33)*.

Drought. Drought is a phase with declining soil moisture and can affect both rain-fed and irrigated agriculture *(55)*. Drought conditions induce stress on plants, thereby reducing their vigour and making them more vulnerable to pathogenic and mycotoxigenic fungi *(24)*. In 2012, about 70% of maize was contaminated with aflatoxin as a result of extreme drought in Serbia *(42)*. In 2003, in six northern regions of Italy, drought coupled with unusual higher temperature caused a shift from fumonisin contamination of maize, caused by *F. verticillioides,* to aflatoxin contamination caused by *Aspergillus* spp. *(24)*. Another example is the higher incidence of *A. flavus* in the southern United States in 1977 and 1983 *(71)*. Water deficits not only raise the concentration of mycotoxins in food and feed *(71)* but also that of leached herbicides, fungicides, and pesticides, as water levels drop in water bodies. In addition to mycotoxins, heavy metals also pose a great threat to food and water safety. Azevedo et al. *(3)* evaluated the effect of drought on the level of accumulation of methylmercury (MeHg), a neurotoxicant, in different fish species in southeastern Brazil and noted a 20% increase in MeHg concentration in muscle tissues of fish under drought conditions, compared with the previous year when drought was not experienced.

NATURAL CALAMITIES

Natural calamities are sudden extreme hydrological, geophysical, meteorological, or climatological events, usually occurring for a short period of time and impacting a relatively small area at once *(60)*. Natural calamities encompass such events as tropical cyclones or hurricanes, monsoons, tsunamis, tornadoes, and wildfires *(27),* and their occurrence, intensity, and frequency are greatly influenced by climate variability *(71, 85)*. Since 1880, 2010 was the second year with the largest recorded number of natural disasters *(34)*. That year was marked by a deadly Russian heat wave, the warmest year for Canada, southwest Australia's driest year, Pakistan's biggest flood, the second-hottest summer in the United States, devastating drought and wildfires in the states of Texas, New Mexico, and Arizona, and historic flooding in the state of North Dakota *(34)*. Events, such as tropical cyclones, tsunamis, and monsoon seasons, are often accompanied by increased precipitation and severe flooding. Altogether, they pose a threat to food safety. As recorded in 1999, flooding caused by Hurricane Floyd in the coastal regions of North Carolina and New Jersey, engendered increased fungal infections, affecting both agriculture and human health *(71)*. Following Hurricane Katrina in the United States, the Centers for Disease Control and Prevention reported an outbreak of gastroenteritis, among which two cases were caused by toxigenic *V. cholerae* O1 *(35)*. In 2004 in Bangladesh, two monsoon-related floods led to large outbreaks of diarrheal disease, with cholera being the most common disease outbreak, followed by infection by enterotoxigenic *E. coli* *(35)*. In cases of hurricanes and storms, where severe winds are involved, the air currents are thought to help in the long-range transportation of causative agents, such as fungal spores of toxigenic fungi *(35)*. Natural calamities do not always have a direct impact on food safety and can indirectly affect the safety of crops and commodities following flooding, droughts, or fires. For instance, wet paper labels on canned foods *(35)* may harbor dangerous bacteria and molds, resulting in foodborne disease outbreaks. Moreover, a power cut can lead to the disruption of chilling, freezing, and cooking systems, eventually encouraging the proliferation of pathogenic and spoilage microorganisms, and leading to foodborne illness *(35)*. Heat dissipated from wildfires and volcanic eruptions can activate food spoilage bacteria, and the toxic fumes may contaminate food causing food intoxication *(35)*. Coronavirus disease 2019 is a pandemic that has been attributed to zoonotic transmission of severe acute respiratory syndrome coronavirus 2, potentially from a bat to humans *(70)*. It can, thus, be hypothesised that natural disasters, such as wildfires, can force feral animals and exotic mammals that are vectors or carriers of pathogens to escape their natural habitat. As a result, new strains of well-known pathogens or emerging pathogens may eventually enter the human food chain.

APPROACHING THE CLIMATE CHANGE PROBLEM: MITIGATION AND ADAPTATION

According to many scientists, the CO_2 emission level should be halved over the next 50 years to be able to monitor greenhouse global warming *(21)*. Hence, immediate response is key to prevent the worst scenarios. There are two ways to deal with the threat of climate change: (i) mitigation, which is taking actions to reduce GHG emissions and (ii) adaptation, which is altering human behaviors to adjust to the inevitable climatic changes *(21)*. Some major actions for climate mitigation include increased energy efficiency, the expanded use of renewable energy, and slower deforestation *(21, 32),* while adaptation includes actions, such as the building of rainwater storage systems and the reinforcement of protective levees at coastal areas, among others.

Improved energy efficiency. Improving energy efficiency is the easiest and quickest approach for the reduction of GHG emissions *(21)*. In the best interest of everyone, countries and political leaders should cooperate in reducing CO_2 emission. Unfortunately, not all countries have the political will to participate *(21)*. Because money is often an effective motivator, a carbon tax can be put in place for energy sources that release more CO_2 in the atmosphere *(21)*. As such, the more the energy consumed, the greater the tax to be paid, thus providing an incentive to individuals to be more energy efficient. The government can also encourage individuals to reduce their energy consumption by providing monetary incentives for energy conservation *(21)*. Of course, this will encourage companies to bring forward more energy-efficient vehicles and appliances. Sweden, Finland, Norway, and The Netherlands have already adopted the idea of a carbon tax *(21)*. However, in some countries such as the United States, the taxes may represent a larger percentage of the income of poor people *(21)*. Transportation is one of the largest users of energy in the world. Hence, there is a need to tackle fuel efficiency and to encourage people to go for smaller and lighter cars. For example, hybrid cars are a modern approach, where the energy lost during braking is then stored and used during acceleration *(21)*. Moreover, in 1970s, when fuel was restricted from the Middle East, automakers had to nearly double the average efficiency of automobiles, and this resulted in a CO_2 fall from 4% to between 1 and 2% yearly *(21)*. In agriculture, good agricultural practices should be inculcated. For example, techniques can be developed to capture CH_4 from landfills or animal wastes for electricity *(21, 32)*.

Transformation of energy. To substantially reduce GHG emissions, drastic changes need to be made. One major approach is the shift from the carbon economy to a sustainable energy economy *(21, 32)*. Alternative energy sources are solar energy, which can be used in photovoltaic cells, hydropower to produce hydroelectricity, wind energy harnessed by wind turbines and wind farms, and geothermal energy from rocks for the production of electricity, biofuels, and nuclear power *(21, 32)*. For instance, hydropower produces about 24% of the world's electricity, and wind could supply 40 times the current demand for electricity and about 5 times the global consumption of power *(21)*. However, they also have certain drawbacks. For example, wind farms are expensive, while nuclear power can have compromised safety aspects. Nevertheless, those need to be tackled with less expensive or fail-safe designs to reduce the possibility of catastrophic accidents and for safe disposal of radioactive wastes. Other approaches are carbon sequestration in natural systems, such as the soil, through large-scale reforestation, the increase of organic matter in the soil, and farming techniques, such as no-till farming and crop rotation and research *(21, 32)*.

Adaptation. Alongside mitigation, adaptation should also be considered, despite reductions in GHG emissions, temperatures will keep rising due to the already present GHGs *(21)*. Thus, nations should prepare for the changes. Adaptation can be a costly process, but as it is said, prevention is better than cure, and planning ahead will spare more deaths and destruction *(21)*. Some examples of adaptation are building of rainwater storage systems to alleviate damage caused by floods, with the water being reused during drier periods, reinforcement of protective levees on coastal areas, the development of crop strains that require less water and soil moisture, planting of crops earlier, and moving farms to more climatically hospitable areas *(21, 32)*. This will be best achieved though cooperation among individuals and countries to tackle this climate agenda.

CONCLUDING REMARKS

It is anticipated that climate change and related phenomena will increasingly threaten the safety of the food supply and bring about a steady rise in the incidence of foodborne infection and intoxication in the coming years. This urgently calls for more interdisciplinary research and concerted efforts among food scientists, public health officers, epidemiologists, veterinarians, meteorologists, and statisticians to better understand and address the challenges of climate change and food safety.

Thanks to global foodborne disease surveillance programs, it is now possible to get real-time updates on the occurrence of any foodborne disease outbreaks in most parts of the world. However, it is additionally important that longitudinal studies are carried out in most developing and developed nations to gather large epidemiological data sets to ascertain relationships between foodborne outbreaks and climate phenomena. Country leaders should provide support to government-owned public health laboratories to focus on active surveillance systems and early detection methods. Automated and high-throughput methods of detection of pathogens, toxins, and chemical residues in food are needed for enhanced monitoring of contamination. Genotype-based approaches to surveillance of food pathogens, such as use of real-time PCR and whole genome sequencing, also need to be widely implemented to enhance tracing and tracking of foodborne illnesses. As such, any emerging foodborne disease trends or otherwise unnoticed outbreaks may be detected in almost real time. Moreover, data sharing among different sectors or ministries and timely translation of research outputs are essential.

Empowerment of the different actors in the food chain to implement food safety management programs in the production systems is also key. In addition to law enforcement, a critical review of existing food laws and standards is also needed in order to adapt to emerging risks and threats. Hence, developing food safety preparedness plans in the event of natural disasters should also be a national priority for every country. Finally, education and awareness campaigns on food safety and health promotion targeting the general population should not be overlooked. Universities, as think tanks, should wield a greater role in education, training, and outreach on the food safety risks linked to climatic factors and climate change, while at the same time building capacity in risk assessment and management. The coronavirus disease 2019 pandemic is a concrete example of a food contamination issue that had resulted in an unprecedented epidemic of a global proportion. Indeed, risk analysis constitutes the sine qua non for science-based decision making by stakeholders in the different agrifood sectors, all with the view to devising approaches for "climate proofing" our food systems.

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